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The Effect of Weather on Soviet Wheat Production

Dec. 1980

R. Robert Rapp



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To estimate the effect of climate on Soviet wheat production, this study devises formulas that calculate variability of wheat production in three major areas: Southwest Ukraine, South Ukraine, and Kazakhstan-West Siberia. Weather conditions in these three areas have a major influence on the total production of wheat in the USSR. Wheat grows best in Southwest Ukraine when it experiences a cool fall, a moderate winter, and a warm spring with normal moisture. Wheat grows best in South Ukraine when the winters are warm and when it is cool and dry in June. In Kazakhstan and West Siberia, abundant crops of spring wheat depend on good rainfall in late spring and early summer. It is concluded that if no major changes in weather patterns occur, the Soviet Union will experience adverse weather, and lower wheat production, in at least one year out of every four. The weather in one year in twenty will cause disastrously low production of wheat. (JH)

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PREFACE

This report documents the findings of a Rand study undertaken to estimate the probable effect of future climatic conditions on wheat production in the Soviet Union. Recent data were used to develop weather-yield relationships, which were then applied to long series of past weather data to develop as extended a climatic series as possible. This climatic series was then extrapolated into the future in the context of three alternative scenarios. The report should be of interest to agrometeorologists and to analysts and planners concerned with Soviet agricultural economics.

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SUMMARY

When bad weather has damaged its wheat crops, the Soviet Union during the past several decades has turned to the West for help. Whereas moderate purchases of wheat have benefited the U.S. economy, larger ones have raised serious political and economic problems. To manage its own supplies effectively, the United States needs to anticipate future failures of Soviet wheat production.

Although many statistical models relate climate to crop yield, none adequately copes with the restricted kind of data we have concerning Soviet temperatures and precipitation. To estimate the effect of climate on Soviet wheat production, this study devises formulas that calculate variability of wheat production in three major areas: Southwest Ukraine, South Ukraine, and Kazakhstan-West Siberia. Southwest and South Ukraine account for one-fourth of the winter wheat production in the Soviet Union, and the rest of its winter wheat comes mainly from regions immediately to the north and east of this area. In addition, Kazakhstan-West Siberia produces more than one-half of the Soviet Union's spring wheat, and the remainder comes largely from Volga and Ural regions that have similar climates. As a consequence, weather conditions in these three areas significantly influence the total production of wheat in the USSR.

This study relies upon limited data derived from two sources. Information concerning Soviet wheat production comes from *USSR Grain Statistics: National and Regional, 1955-1975*, and information concerning Soviet precipitation and temperature comes from World Weather Records supplied by the National Center for Atmospheric Research. Unfortunately, information about wheat production coincides with information about weather conditions for only the period between 1955 and 1973.

We find that wheat grows best in Southwest Ukraine when it experiences a cool fall, a moderate winter, and a warm spring with normal moisture. Though the weather causes distinct oscillations in yearly wheat production, no predictive patterns emerge from these

variations. For this area, we estimate wheat production using the following formula:

$$\hat{y} = 0.6683 - 0.0031 T_N + 0.0328 T_W + 0.0162 T_{Mr} - 0.0044 M_{Ap}$$
$$- 0.0027 M_{My} - 0.0089 T_{Jn} - 0.0048 M_{Jn}$$

In this formula,

\hat{y} = estimated deviation in yield caused by weather conditions.
T = mean temperature in November (T_N), March (T_{Mr}), and June (T_{Jn}), or the lowest mean monthly temperature in the winter months of December, January, and February (T_W).
M = deviation of soil moisture from optimum in April (M_{Ap}), May (M_{My}), and June (M_{Jn}).

We find that wheat grows best in South Ukraine when the winters are warm and when cool, dry weather occurs in June. No predictive pattern emerges from yearly variations in wheat production. Wheat production in this area can be estimated with the following formula:

$$\hat{y} = -0.0105 \delta T_N + 0.0439 \delta T_W + 0.0472 \delta T_{Mr} - 0.0909 \delta T_{Ap}$$
$$+ 0.0003 \delta T_{My} - 0.1076 \delta T_{Jn} + 0.0391 \delta T_{Jy} + 0.0026 \delta P_W$$
$$- 0.0059 \delta P_{Ap} + 0.0016 \delta P_{My} - 0.0020 \delta P_{Jn} + 0.0017 \delta P_{Jy}$$

In this formula,

\hat{y} = estimated deviation in yield caused by weather conditions.
 δT = deviation of the monthly mean temperature from the 1955-1973 monthly means in November (T_N), March (T_{Mr}), April (T_{Ap}), May (T_{My}), June (T_{Jn}), and July (T_{Jy}), or deviation of the lowest winter temperature from the 1955-1973 winter mean temperature (T_W).

δP = deviation of the total monthly precipitation from the 1955-1973 monthly mean totals in April (P_{Ap}), May (P_{My}), June (P_{Jn}), and July (P_{Jy}), or deviation of the average winter precipitation--August through March--from the 1955-1973 average for the season (P_W).

In Kazakhstan and West Siberia, abundant crops of spring wheat greatly depend upon good rainfalls in late spring and in early summer. Weather causes greater variation in the wheat crop here than in other areas of the Soviet Union. Moreover, a pattern of alternating years seems to emerge: if one season produces a good crop, the next will probably produce a poor one. For this area, we estimate wheat production with the following formula, which employs the same notations used in computing wheat production in South Ukraine:

$$\begin{aligned}\hat{y} = & -0.0017 \delta T_{Mr} - 0.0011 \delta T_{Ap} - 0.0007 \delta T_{My} - 0.0005 \delta T_{Jn} \\ & - 0.0008 \delta T_{Jy} + 0.0023 \delta P_W + 0.0121 \delta P_{Ap} + 0.0049 \delta P_{My} \\ & + 0.0042 \delta P_{Jn} + 0.0005 \delta P_{Jy}\end{aligned}$$

Though reliable predictions of Soviet wheat crops rest upon the kind of long-range weather forecasting that we currently do not have, several broad patterns nevertheless do emerge. If no major changes in weather patterns occur, we can expect that the Soviet Union will experience adverse weather--and hence lower wheat productions--in at least one out of every four years. Moreover, the weather in one year out of twenty will cause disastrously low productions of wheat.

ACKNOWLEDGMENTS

I wish to express my thanks to Gail M. Burkholz for handling all of the computer work and preparing the appendix, to Roy Danchick for locating several useful computer programs and adapting them to our needs, and to Frank Murray and Allan Abrahamse for their helpful reviews. I am also grateful to Felix Kogan, who emigrated from the USSR in 1979 and who is now at the University of Missouri at Columbia, for giving me a three-day crash course in Soviet agrometeorology.

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I. INTRODUCTION

PURPOSE AND PLAN OF THE STUDY

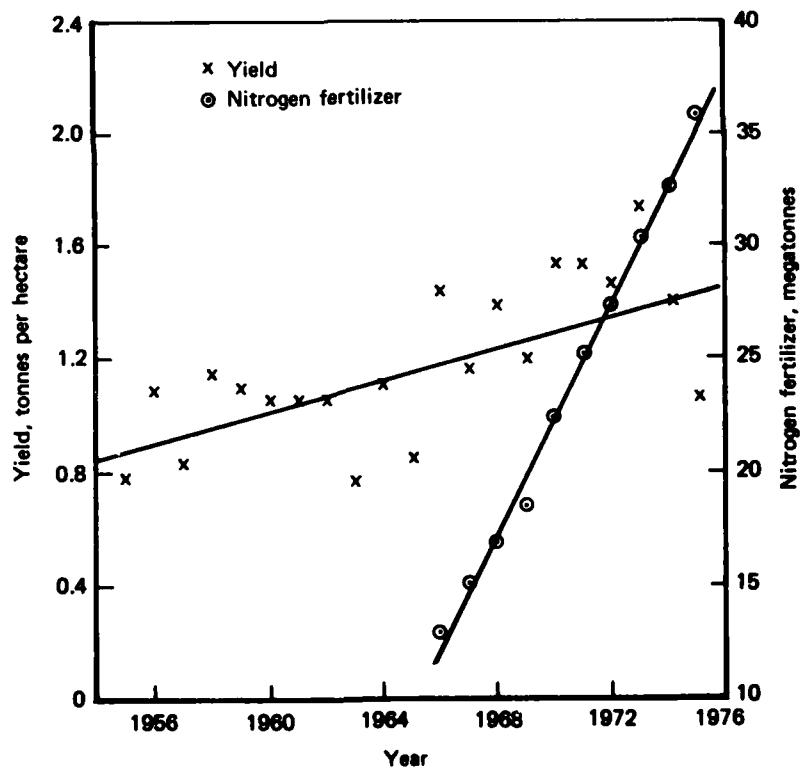
The objective of this study is to provide a method for estimating the variability of Soviet grain production caused by variation of the climate. The available crop data cannot provide such estimates because the record is not long enough and improved technology has greatly increased the productivity of the land. To eliminate these shortcomings of the data, it is necessary to eliminate the effect of technology and provide a model that will relate as much as possible of the residual variation to weather factors. This model is then applied to as many past years of weather data as are available.

Technological improvements include improved management practices, improved genetic qualities of the seed, and increased use of fertilizer. Direct measures of the effect of technology are not readily available, but by assuming that technology has advanced with time, time serves as a surrogate for a measure of the effects of technology. Because this is only an approximation to the true effects of technology, there will be some residual variation which will not be included in a trend analysis.

Assuming that a trend analysis can capture the bulk of the variation resulting from improved technology, climatic variables can be statistically related to deviations from the trend. Surveys of the literature by Baier (1977) and McQuigg (1975) present a great many models to relate climate to crop yield. Many of these models include measurements of daily meteorological variables and measurements of the state of the crop at various times. Models of such detail are not suitable for this study. In order to have a model that is applicable to weather data that go back in time to the last decade of the nineteenth century, it is necessary to restrict the meteorological variables to mean monthly temperature and total monthly precipitation.

TECHNOLOGY TRENDS

It is apparent from studies in many parts of the world that new technology has raised the level of wheat production (McQuigg, 1975). Thompson (1969) pointed out that the use of nitrogen fertilizer has had a profound effect on the production of cereal grains. Use of fertilizer plus improved strains of grain and better farm machinery have raised the yield per hectare from 30 to 50 percent in both the United States and the USSR. A major difference is that the rise in output began in this country about 1950, but not in the USSR until about 1960. Figure 1 shows the wheat yield and the delivery of nitrogen fertilizer in the USSR. The increase in yield as the fertilizer increased is apparent.



The most generally accepted method of accounting for improved technology is to use time as a surrogate. In general, the procedure is to fit some sort of trend line (a correlation of yield with time) to the yield data and assume that the trend results from technological advance and that deviations from the trend are due to weather and other factors that influence yield. McQuigg (1975) suggests that 70 to 80 percent of the yield variation is due to technology, 12 to 18 percent due to weather factors, and 5 to 10 percent due to "random noise." Kogan (1977) analyzed grain production in the Soviet Union with data from experimental farms (strain selection stations) and operational agricultural enterprises (Kolkhoz and Sokhoz). He found a linear trend in yield from 1945 through 1975 with the experimental farms outproducing the operational farms by 30 to 100 percent.

One of the difficulties of using trend analysis to account for technological advances is that the sample may not include a wide enough variety of weather situations to fully eliminate the effect of weather. In a small sample, a few bad weather years in the beginning of the sample period and a few good years at the end may produce the appearance of a trend where none exists. Lack of more concrete measures and the obvious rise in wheat yield with the production of fertilizer lends credence to the concept of using trends with time as a surrogate for improved technology. Thompson (1969), using U.S. wheat yield data from 1920 to 1968, showed a rather flat curve for 1920 to 1940, a transition from 1940 to 1950, and a sharp rise from 1950 to 1968. Kogan's data from 1945 to 1975 indicate a fairly steady rise, but he smoothed his data by moving averages and then fitted a straight line. A different analysis might have shown a slightly more accelerated growth after 1950.

Despite its shortcomings, trend analysis appears to be the best method for estimating gains from technology. Figures 2, 3, and 4 show the yield data as a function of time for the Southwest Ukraine, the South Ukraine, and Kazakhstan, respectively. For the Ukraine, a quadratic trend appears to be the best fit; for Kazakhstan and West Siberia, a linear trend appears best. The rather large variance

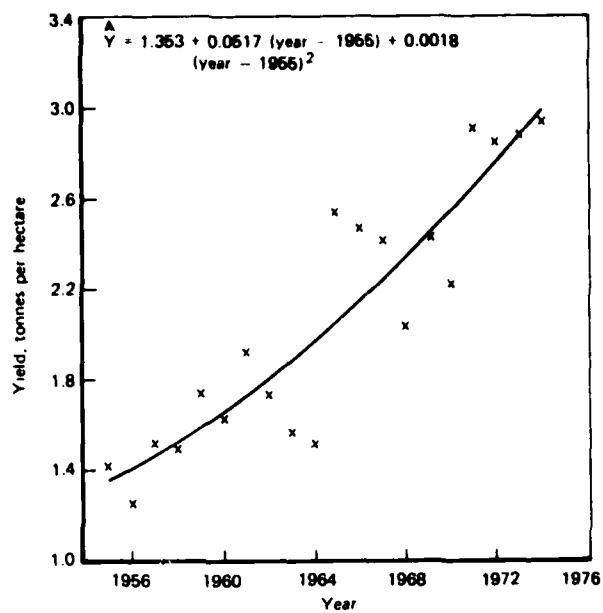


Fig. 2 — Time trend of winter wheat yield,
Southwest Ukraine

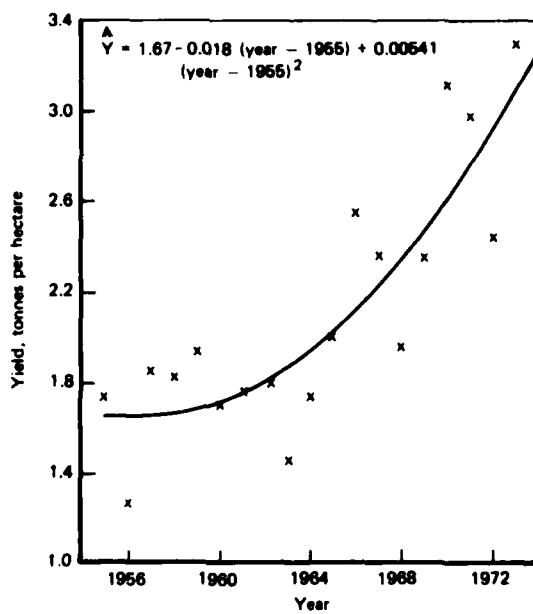


Fig. 3 — Time trend of winter wheat yield, South Ukraine

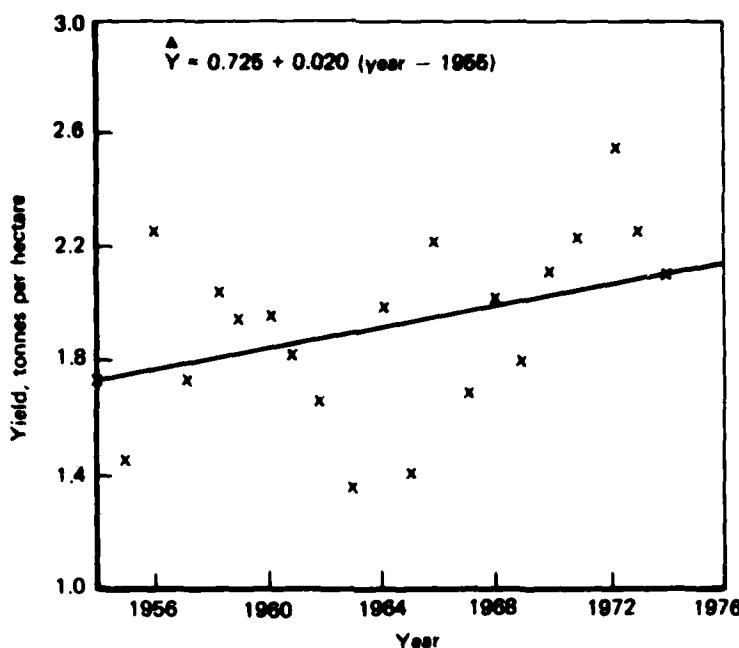


Fig. 4 — Average Kazakhstan and West Siberia trend analysis

about the trend in Kazakhstan and West Siberia may well obscure any real second-degree terms in time. For purposes of a study of weather effects, we will use differences from the trend lines in Figs. 2, 3, and 4 as the basic yield variable. A more general discussion of variability will appear in a later section of this report.

THE AVAILABLE DATA

The yield data for the Soviet Union that are available to this project are published in *USSR Grain Statistics: National and Regional, 1955-1975*, Economic Research Service, Statistical Bulletin No. 564 (ERS, 1977). This booklet consists of 21 tables showing the production of all types of grain in many different forms. We have chosen to concentrate on wheat production and to use the yield per hectare as a measure that can best be related to weather (Thompson, 1975). Table 15 of ERS Bulletin No. 564 gives the yield of winter wheat, by region, for 19 regions and presents a map showing that winter wheat is produced primarily in European Russia and the Ukraine. Table 18 of the Bulletin gives the production of spring

wheat for the same regions, and the chart shows that spring wheat is produced largely in the Volga region and the Asiatic parts of Russia. To develop an understanding of the relationships of weather to wheat yield, we have made a rather detailed study of winter wheat in the Ukraine and a less detailed study of spring wheat in Kazakhstan.

The available weather data are the World Weather Records, which were made available to us on magnetic tape by the National Center for Atmospheric Research. From these tapes we extracted total monthly precipitation and mean monthly temperatures for selected stations in the Soviet Union. Data for most of these stations covered the period from 1882 to 1973.

The relation between weather and crop yield has been studied extensively in the United States using good yield and weather data for 30 to 50 years (Thompson, 1975). McQuigg (1975) has presented an annotated bibliography of wheat-yield/weather studies. Some of these studies used experimental farms with special weather monitoring equipment; others used areal averages of yield and weather data. In this project, there is the problem of using only one weather station to relate weather to the average yield over a large region. Moreover, there are only 19 years for which the yield and weather data overlap. Such a small sample makes it imperative to choose weather variables with extreme care to minimize the possibility of producing statistical relationships that are not truly representative of the long-term relation between yield and weather. The fact that the weather data may not be representative of the area, combined with the need to be parsimonious in the choice of weather variables, will result in a model that can capture only the major features of the crop/weather relation. We hope to be able to delineate weather patterns that produce bumper crops and to differentiate from patterns that produce reduced yields. We will not produce a method for predicting the yield with any certainty.

THE WEATHER VARIABLES

Many investigators have shown that temperature and precipitation are closely related to yield; however, some detailed investigations have used temperature and measures of available soil moisture with good success. To use precipitation as a variable over a large area, it is necessary to have a measure of the average precipitation over the area. Rainfall at a single station is usually too variable to give a good measure of available soil moisture. Since area averages are unavailable for the regions of the Soviet Union for which crop data are reported, it was deemed necessary to find a more stable moisture variable than single-station rainfall. The water balance calculations of Thornethwaite and Mather (1957) provide a means for smoothing out the time variations in precipitation. The method used is presented in the appendix. The index used is the deviation of the soil moisture from an assumed field capacity of 300 mm of water. This cannot be considered a measure of available moisture but only an index of the possible variations in soil moisture. Correlations of this monthly index between stations is not as good as we might wish but is far better than correlations of monthly mean rainfall.

Monthly mean temperatures are a much more stable measure than total monthly precipitation. Correlations between stations are relatively good, and the monthly mean temperature at a single station can be considered a fairly good index of regional temperature variations.

PLAN OF THE REPORT

Section II reports on a fairly detailed study of winter wheat production in the Southwest Ukraine. Section III reports on much less detailed studies of the South Ukraine and Kazakhstan. The South Ukraine study tests a slightly different statistical approach and the Kazakhstan study deals with spring wheat. Section IV is a broad discussion relating yield variability to weather variability for many regions of the USSR. Section V presents some climatic scenarios and their possible effects on wheat production. A summary of the overall effect of climate on wheat production--based on what has been learned in this study--concludes the body of the report. An appendix describes the procedures used in the methodology.

II. THE SOUTHWEST UKRAINE

THE AREA AND ITS CLIMATE

For purposes of reporting wheat yields, the Ukraine is divided into three subsections: Southwest, South, and Donets-Dnieper. We chose--arbitrarily--to study the Southwest section in detail. This region includes the cities of Lvov and Kiev, parts of the Dniester River valley along its southwest border, and parts of the Dnieper River valley along its northeast border. Between these two river valleys the land rises to between 200 and 500 meters above sea level. The Carpathian mountains rise rather steeply to as much as 2000 meters from the south bank of the Dniester.

The area is classified by the Grigor'yev-Budyko system as humid and warm, with moderate winters (Lydolph, 1977). The humidity--or more properly the aridity--index is a measure of potential evapotranspiration divided by annual precipitation. The temperature index is the sum of the temperatures during the period when the daily mean temperature is greater than 10°C, and the winter character--in this case moderately mild--is based on the mean January temperature. Because the Southwest Ukraine is the only wheat-growing region classified as humid, we expect the moisture variables in this area to affect crop yield differently from the remainder of the Soviet wheat areas, which are considered to have inadequate water.

WEATHER EFFECTS ON WINTER WHEAT

Winter wheat is planted in the fall of the year. The seed germinates before the cold of winter sets in but remains dormant throughout the winter. In the early spring, the plant resumes its growth and develops during the late spring and early summer. Harvest is in late summer, after which the fields are prepared for a new crop.

The first weather problem in the winter wheat cycle is in the harvest of the previous year's crop. If rain delays harvest and

reseeding, there may be insufficient time for the new crop to germinate. On the other hand, if seeding is early or the winter cold is delayed, the plants might grow too large in the fall and be more susceptible to killing freezes in the winter.

No data are available to estimate the effect of seeding time on the following year's harvest, but an effort was made to estimate the effect of winter freezing on the final crop. Plots of yield deviation from the trend were made against the temperature and soil moisture deviation from August through November of the preceding year to search for an index of overgrowth in the fall. The only apparent relation was with November temperatures. High mean monthly temperature in November suggested poorer yields in the following year. As an index of possible freezing winters, we chose the lowest mean monthly temperature among the months of December, January, and February. A plot of November temperature, T_N , against the lowest winter temperature, T_W , with the yield deviation from the trend entered at the intersection appeared to confirm the fact that overgrowth in the fall, coupled with a cold winter, drastically reduced the yield. Figure 5 shows this plot with a dividing line computed from a linear discriminant function analysis. The criterion for choosing two groups to discriminate was that a yield deviation in the lower quartile of the yield deviation distribution was classified as a bad year to be discriminated from all others.

Figure 5 and the discriminant analysis of November and winter temperatures highlight a problem that may well exist with other variables. The problem is one of the possible asymmetric effect of any weather variables on crop yield. High temperature in November followed by a cold winter has a deleterious effect on crops, but low November temperatures followed by a warm winter do not necessarily have a salubrious effect on crops. It is conceivable that there are other weather variables that may have a similar asymmetric effect which has not been accounted for.

If we accept the concept that fall overgrowth and winter freeze kill a certain fraction of the plants, nothing about the weather in

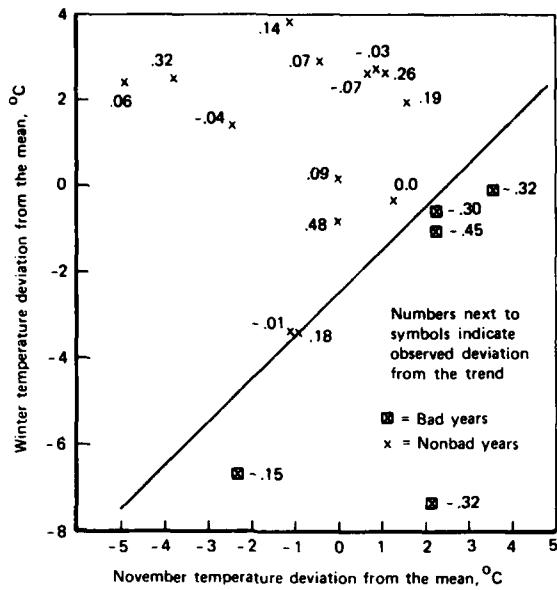


Fig. 5 — Discriminative cases in which part of the wheat crop was frozen during the winter

subsequent months can restore them.* A perfect growing season from March through July can increase the yield of the surviving plants, but the average yield per hectare will be lowered by the loss of some plants.

The plants that survive the winter start their regrowth in the spring. Plots of temperature and soil moisture deficit for March and April against yield showed a definite trend toward higher yields with warmer March temperatures. Figure 6 is a plot of March temperatures, T_{Mr} , against yield deviations. In this figure, the five years that were subject to winter kill by the previous analysis are plotted as squares. The trend toward higher yields with warmer March temperatures is apparent in the remaining 14 years of data. If it is assumed that the winter freeze reduced the final yield by the same amount in all five bad years--a very crude assumption--then the

*According to Felix Kogan (personal communication), the Soviets will plant a spring crop of another type of grain in areas where winter kill has been severe.

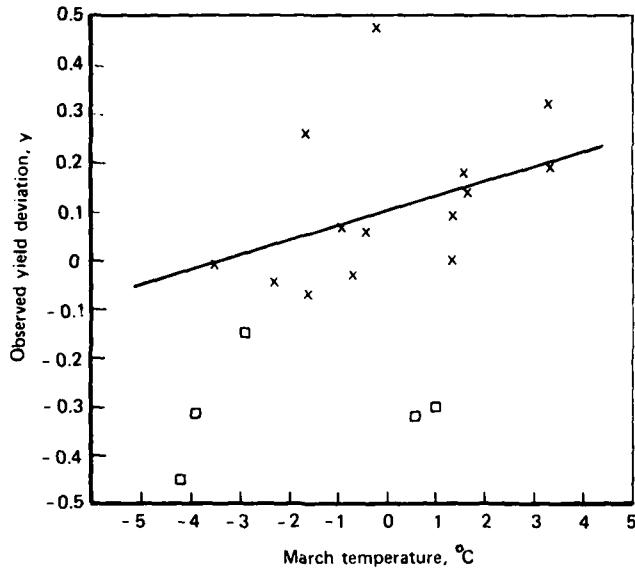


Fig. 6 — Effect of March temperature on wheat yield deviation from the trend showing those cases where part of the crop was frozen

effect of subsequent variables could be estimated by adding this amount of yield deviation to the five bad years. If this is done, the correlation between yield deviation and March temperature is 0.46 and the slope of the regression line is 0.03, i.e., each additional degree of March mean temperature contributes 0.03 tonnes per hectare of grain to the final yield.

Plots of the temperature versus yield deviation for April and May showed no linear correlation between yield and temperature for the 19-year sample and gave no hint of any nonlinear relation. The April and May temperatures were therefore discarded from further consideration. Samples over a wider range of temperatures might have shown significant results.

The moisture deviation plotted against the yield deviation for April and May showed weak linear relationships but suggested that both too much and too little moisture reduced the yield. Using the absolute value of the April moisture deviation, a fair linear relationship with yield deviation was found. For May, the absolute value of difference between the actual moisture deviation and a

moisture deviation of -40 mm gave a fair linear relation with yield deviation. These two moisture variables were therefore included in the set to be tested. They are indications of the excursion of the soil moisture from an approximate optimum amount.

June temperature showed a fairly strong negative correlation with yield. This relationship is similar to that found by other investigators, i.e., warm temperatures during the later stages of growth are harmful. June temperature was chosen as a candidate variable. The June moisture deviation, like that in April and May, suggested that a deviation from an optimum reduced the yield. An optimum of -105 mm was chosen from a plot of moisture deviation against yield deviation, and the absolute value of the difference between moisture deficit and -105 mm was chosen as a variable.

No weather variables in July and August seemed to affect the yield in this sample. This preliminary study of winter wheat culture in the Southwest Ukraine suggested seven weather variates which appear to be related to yield:

T_N	Mean November temperature
T_W	Lowest mean monthly temperature in Dec., Jan., and Feb.
T_{Mr}	Mean March temperature
M_{Ap}	Deviation of soil moisture from optimum in April
M_{My}	Deviation of soil moisture from optimum in May
M_{Jn}	Deviation of soil moisture from optimum in June
T_{Jn}	Mean June temperature

All of these variables showed fairly high correlations with the yield deviations in the 19-year sample at our disposal. Different samples with more widely varying conditions might have produced more variates and might have involved some nonlinear terms. With this small sample, however, more variates would only serve to reduce confidence in the final results. Seven variables to correlate with yield deviation are excessive for a sample of only 19 years. However, the pattern of weather during the year is probably important. The pattern of a good year that emerges from this preliminary survey is:

A cool--but not cold--fall
A winter without excessively cold temperatures
A warm spring with normal moisture
A cool summer with normal moisture

EMPIRICAL ORTHOGONAL FUNCTIONS

The whole process of wheat culture suggests that there are patterns of temperature and moisture as a function of time through the growing season that govern the yield for a particular year. It would be possible to take the seven variables that have been defined and simply construct a multiple regression equation to predict the yield deviation. The use of seven variables to predict 19 values could result in overfitting the available data. Therefore, we have chosen to search for patterns of the seven variables and fit the yield deviation data with just a few of these patterns.

Lorenz (1959) proposed the use of empirical orthogonal functions (EOFs) for statistical weather predictions.* The procedure is to rotate the coordinate system of the original measurements to obtain a set of new independent variables which are uncorrelated. Suppose there are N weather variables, w , measured for M years. These measurements form an $M \times N$ matrix, W . Let X be an $M \times N$ matrix of transformed variables. Lorenz shows that it is possible to find an $M \times N$ matrix, Q , such that

$$X = WQ \quad (1a)$$

$$W = XQ' \quad (2a)$$

and

* This statistical technique, also known as the method of principal components, is described in detail in Cooley and Lohnes (1971). The analysis used here was adapted from Lorenz's work.

$$QQ' = I$$

where I is the identity matrix and the prime denotes the transpose of the matrix.

The matrix equations (1a) and (2a) can also be written as algebraic equations. If w_{ij} is the j th variable for the i th year, x_{ik} is the k th new variable for the i th year, and q_{jk} are the elements of the transformation matrix, Q ,

$$x_{ik} = \sum_{j=1}^N w_{ij} q_{jk} \quad (1b)$$

and

$$w_{ij} = \sum_{r=1}^N x_{ir} q_{rj} \quad (2b)$$

The transformed variables, x_{ik} , have the following properties:

1. Each is a linear combination of the original variables.
2. The sum over k of the squares of coefficients, q_{ik} , is unity.
3. The sum of the variances of the x 's is equal to the sum of the variance of the w 's.

The numbering of the new variables is chosen such that X_1 has the largest proportion of the total variance, X_2 the next largest, and X_N the least proportion of the total variance.*

Variation is information. An observation that yields the same result every time it is made has no use as predictor. An observation

* Henceforth we employ the notation \underline{x}_k to signify the column vector whose elements are x_{ik} , $i = 1, 2, \dots, M$.

that changes a great deal may be a good predictor. The first x variable may be thought of as the single observation that can be derived from the w 's containing the most information. The second x variable may be regarded as the single observation containing the most of what information remains. Similar statements can be made about X_3 , X_4 , and so on. The entire set of x 's contains exactly the same amount of information as the set of w 's, but the information is distributed among the variables in a more convenient way. In particular, most of the information in the entire set of w 's may be contained in just a few of the x 's. In addition, there is no overlapping of information among the x 's because they are uncorrelated.

Using the seven variables listed in the preceding section, with Kiev data for the years 1955 through 1973, EOF's were determined (see the appendix). Table 1 lists the proportion and cumulative percent of variance accounted for by each EOF. Note that less than one percent of the variance of the w_{ij} is accounted for by the last three EOF's. We would therefore expect that the w_{ij} could be adequately reconstructed from only the first four x_{ik} 's.

Table 1
PERCENT OF VARIANCE

EOF Vector	Percentage of Variance	Cumulative Percentage Variance
1	51.43	51.43
2	34.23	85.66
3	12.63	98.29
4	1.00	99.29
5	0.34	99.63
6	0.26	99.89
7	0.11	100.00

Table 2 lists the values of the first X_k 's for the years 1955 through 1973, along with the yield deviation for these years. At the bottom of each column of the X_k , the correlation and the regression

Table 2
CORRELATION OF FOUR TRANSFORMED VARIABLES WITH YIELD DEVIATION

Year	X_1	X_2	X_3	X_4	y	\hat{y}
1955	13.88	14.10	3.42	-2.56	0.07	0.07
1956	15.58	31.38	-5.41	6.34	-0.15	-0.24
1957	-7.57	10.58	17.64	-0.69	0.06	0.16
1958	-5.40	-21.68	-10.55	-3.27	-0.03	0.05
1959	12.11	-29.58	9.89	-2.77	0.14	-0.04
1960	-26.82	-4.93	1.33	-0.08	-0.04	0.15
1961	-4.38	-20.61	-1.66	-2.60	0.19	0.05
1962	8.82	18.75	-4.17	-2.79	-0.07	0.10
1963	-26.31	-24.21	-22.03	6.12	-0.32	-0.22
1964	41.46	-33.20	11.66	5.12	-0.45	-0.52
1965	-31.40	18.62	1.15	0.36	0.48	0.24
1966	-10.37	17.30	4.40	-4.18	0.32	0.29
1967	-27.78	-2.73	-4.81	1.63	0.18	0.08
1968	9.35	-4.86	3.26	0.86	-0.30	-0.09
1969	7.45	26.36	-3.38	3.24	-0.01	-0.09
1970	62.05	7.87	-14.79	-2.10	-0.32	-0.31
1971	-10.54	8.67	-11.42	-3.11	0.26	0.18
1972	-9.54	7.71	-4.16	-1.18	0.09	0.12
1973	-10.49	-1.84	28.92	2.42	0.00	0.05
(a)	-0.592	0.267	0.140	-0.521		
(b)	23.02	18.78	11.41	3.22	0.233	0.199
(c)	-0.0060	0.0033	0.0029	-0.0377		

^aCorrelation.

^bStandard deviation.

^cSlope.

coefficient with the yield deviation are listed. Note particularly the high correlation with X_4 . Although X_4 contributes only one percent of the variation of the independent variables, it represents a temperature pattern which has a major effect on crop yield. Positive departures from normal in November and June, coupled with negative departures from normal in winter and March, would produce a high negative contribution to crop yield deviation from X_4 . Although X_1 , X_2 , and X_3 are heavily weighted with the moisture variable, it is difficult to interpret the pattern climatically because of the

decision to use deviations from an arbitrarily chosen optimum. The multiple regression using the four X_k 's that account for more than 99 percent of the variance of the seven original variables is

$$\hat{y} = -0.0060x_{i1} + 0.0033x_{i2} + 0.0029x_{i3} - 0.0377x_{i4} \quad (3)$$

where \hat{y}_i is the yield deviation estimate from the x_{ik} . The multiple correlation coefficient is 0.844, which indicates that the four transformed variables account for 71 percent of the variance of the deviations of the yield from the trend.

Figure 7 is a plot of \hat{y} against y . The standard error of estimate is 0.12 tonnes per hectare and the two dashed lines are two standard errors on either side of the best fit line. If we take ± 0.15 as dividing lines for the upper and lower quartiles and estimate yields as below normal, normal, or above normal based on these approximate quartile divisions, we would have the breakdown shown in Table 3.

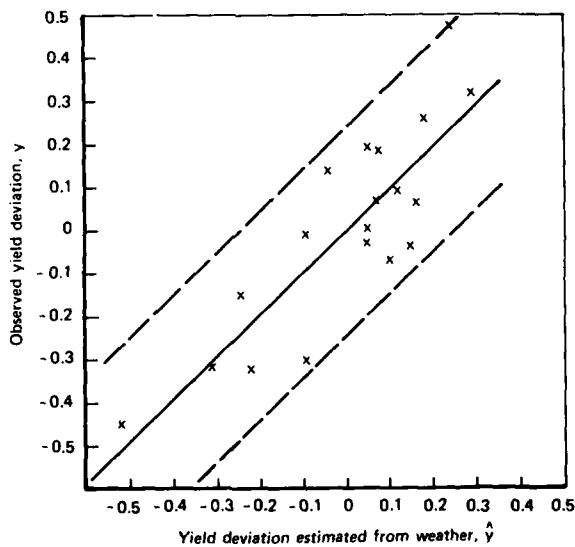


Fig. 7 — Comparison of estimated yield deviation from the trend with observed yield deviation from the trend

Table 3
CONTINGENCY TABLE
(Estimated versus observed)

Estimated \hat{y}	Observed y		
	Below	Normal	Above
Below	3	1	0
Normal	1	8	1
Above	0	2	3

Table 4 compares McQuigg's (1975) estimates of the fraction of the variance of total yield due to technology, weather, and random noise with the fractions of variance obtained in this analysis. The total variance of the yield over the 19 years was 0.276 (tonnes per hectare)². The variance about the trend was 0.054 (tonnes per hectare)²; therefore the amount of variance accounted for by the trend was 0.222, or 80.4 percent of the total. The regression with the weather variables accounted for 71.3 percent of the 0.054 (tonnes per hectare)² not accounted for by the trend. This amounted to 0.039 (tonnes per hectare)², or 14.0 percent of the total variance. The remaining percentage, 5.6 percent, is unexplained variance.

Table 4
McQUIGG VERSUS PRESENT ANALYSIS
ESTIMATES

Percent Variance Due to	McQuigg Estimates	This Analysis
Technology	70-80	80.4
Weather	12-18	14.0
Random noise	5-10	5.6

We conclude from the magnitude of the multiple correlation coefficient, Fig. 7, and Tables 3 and 4 that fitting the Kiev weather variables to the crop data of the Southwest Ukraine for the years 1955 to 1973 is about as good as can be expected for a weather-yield relation. A later section will deal with a slightly different approach for the South Ukraine for comparison of methods.

The purpose of this study, however, is to show how deviations from a trend or a mean might have occurred over past years. If we look only at deviations from the trend for the years 1955 to 1973, the weather variables account for about 72 percent of the variance, leaving 28 percent due to random noise. If, however, we apply the yield deviation prediction equations to other years, we cannot expect them to do as well as they did on the years to which they were fitted. Ideally, an independent sample of years should be tested. Lacking such a sample, we can only estimate the expected degradation.

Lorenz (1959) developed a method for making such estimates. Let S_o be the fraction of variance of a population which is accounted for by some relationship and R_o be the residual variance so that $S_o + R_o = 1.0$. Let S' be the reduction in variance obtained in a sample of size N with M independent variables and S'' be the reduction in variance when the same equation is applied to an independent sample. Lorenz then shows that:

$$S' \approx S_o + \frac{M}{M - 1} R_o \quad (4)$$

and

$$S'' \approx S_o - \frac{M}{N + 1} R_o \quad (5)$$

Since $S_o + R_o = 1$, these can be written

$$S' = 1 + R_o \left(\frac{M}{N - 1} - 1 \right) \quad (6)$$

$$S'' = 1 - R_o \left(\frac{M}{N+1} + 1 \right) \quad (7)$$

From the results of the fit to 19 years and data with four variables, $S' = 0.72$, R_o is found from Eq. (6) to be 0.36, and S_o is 0.64. The remainder of our sample of weather data is 66 years, so a rough estimate of the expected reduction in variance from Eq. (7) is about 0.62. Thus we must expect that the application of Eq. (3) to the early years of data will result in somewhat greater errors than found in the recent sample.

ANALYSIS OF THE ESTIMATED YIELD DEVIATION

Time Series Analysis

Figure 8 is a plot of the deviations in yield, as estimated by Eq. (3), from whatever base may have been "normal" for the period in question. The solid line is the result of applying a five-year binomial smoothing operator which eliminates oscillations with periods of two years or less and reduces the amplitude of oscillations with periods of two to 10 years but maintains the full amplitude of oscillations with periods of 10 years or more. This smoothed curve is shown mainly to emphasize the long-term changes over the years.

The break in the data between 1937 and 1949 is the result of World War II. Occasional missing data were interpolated for other years, but there was so much missing data from 1937 to 1949 that it was impossible to make any reasonable interpolation. There is a hint of long-period oscillation with a maximum in the early years of this century, a minimum around 1930, and a second maximum around 1965. Unfortunately, the missing weather data preclude any possibility of testing the reality of such a long-period oscillation.

The 56 years of data between 1882 and 1937 were subjected to a spectral analysis as outlined by Mitchell et al. (1966). Lag covariances to 18 lags were computed and the resultant series was harmonically analyzed to make spectral estimates for 19 spectral

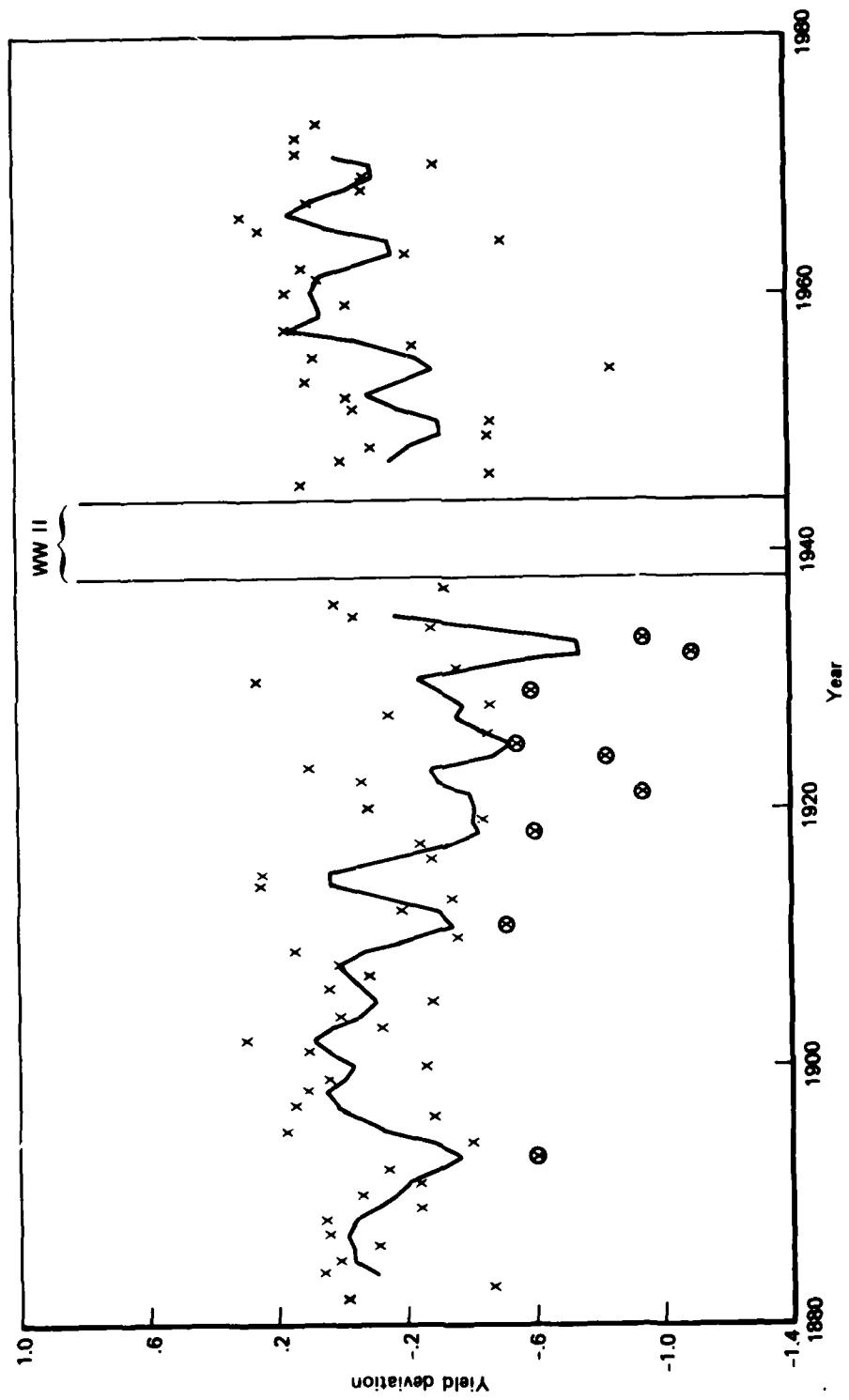


Fig. 8 — Yield deviation due to weather factors, Kiev

intervals. Figure 9 shows the resulting smoothed spectrum. There was a hint of persistence in the data as shown by a lag 1 correlation of 0.22. An estimate of the continuum based on a red noise spectrum with a lag 1 correlation of 0.22 was therefore chosen as a basis for comparison of the peaks in the spectrum. According to Tukey (1950), the smoothed spectral estimates have an error distribution given by χ^2/v , where v is the number of degrees of freedom and χ^2 is the χ^2 distribution with v degrees of freedom. Tukey also shows that $v \approx (2N - m/2)/m$, where N is the number of years in the sample and m is the number of lags in the autocovariance sequence. The heavy solid line on Fig. 9 is the red noise continuum and the dashed curve is the 95 percent confidence limit. Thus, to have any confidence of a real periodicity, the spectral curve would have to extend above this 95 percent confidence limit. Since none of the spectral peaks reach this limit, we must conclude that there are no periodicities shown in this sample.

With a sample as short as this, the resolution of the spectral analysis is very poor for the longer wavelengths. The zeroth

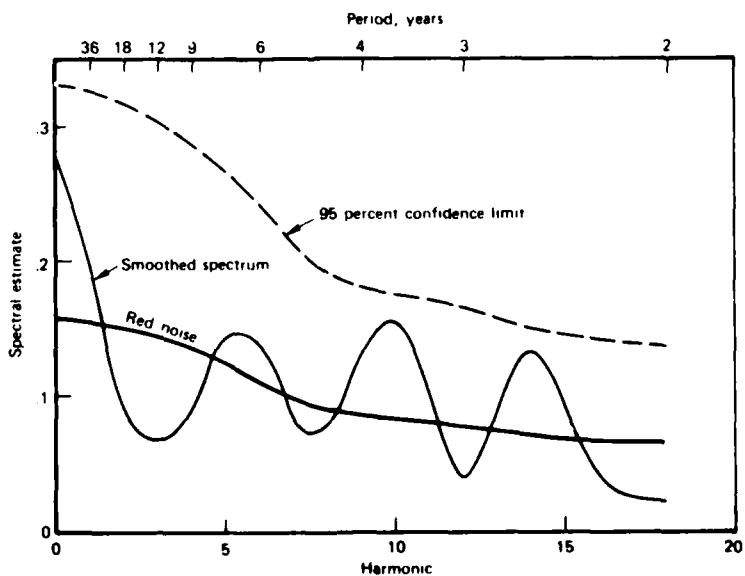


Fig. 9 — Spectral analysis of estimated yield deviation from the trend

harmonic represents an infinite period--which is interpreted as a trend--and the first harmonic represents a 36-year period. No period of oscillations larger than 36 years can be resolved. Resolution could be improved by computing autocovariances for more lags, but this would reduce the number of degrees of freedom and preclude the detection of significant periods. We can only conclude that this analysis shows no significant trend, no significant periodicity, and only a very weak year-to-year persistence in deviation from the trend.

The Causes of Poor Yield

In developing the basic estimation equation, we tried to indicate the patterns of weather which affected the wheat yield. In order to focus on the weather factors which led to estimates of poor yields in this century, we can transform Eq. (3) to an equation in the original variables by means of the eigenvectors. Going back through the variable transformation, Eq. (3) becomes:

$$\hat{y} = 0.6683 - 0.0031 T_N + 0.0328 T_W + 0.0162 T_{Mr}$$

(8)

$$- 0.0044 M_{Ap} - 0.0027 M_{My} - 0.0089 T_{Jn} - 0.0048 M_{Jn}$$

The moisture variables are bilinear. It is necessary therefore to go back to the original moisture excess data to determine whether the value of M is from the wet branch or the dry branch of the distribution. Table 5 give the contribution of each of the seven variables to the final estimate of the yield deviation for eight of the worst years in the period 1882 to 1937. In the moisture variable column, the branch of the bilinear curve is indicated by a D for dry or a W for wet. An examination of Table 5 shows that November, March, and June temperatures played a minor role in the determination of

Table 5
POOR CROP YIELD YEARS IN THE SOUTHWEST UKRAINE

Year	\hat{y}^a	T _N	T _W	T _{Mr}	M _{Ap}	M _{My}	T _{Jn}	M _{Jn}
1911	-0.52	0.000	-0.144	-0.008	-0.051D	0.007D	0.030	-0.359W
1918	-0.59	0.008	0.082	0.011	-0.386D	-0.201D	0.015	-0.123D
1921	-0.93	0.014	-0.003	0.084	-0.515D	-0.259D	0.004	-0.257D
1924	-0.83	-0.011	-0.177	-0.050	-0.431W	-0.044D	-0.026	-0.085D
1925	-0.55	0.005	0.046	0.037	-0.411D	0.227D	0.031	-0.032D
1929	-0.60	-0.007	-0.312	-0.068	-0.132W	0.027W	0.027	-0.136W
1932	-1.10	0.007	-0.128	-0.071	-0.150W	0.038W	0.006	-0.799W
1933	-0.94	0.000	-0.092	-0.013	-0.274W	-0.069W	0.032	-0.528W

\hat{y} = estimated yield deviation.

estimated yield deviation for these eight years. In 1929 the cold winter was a major factor, and the winter temperature had a large effect in 1911, 1924, and 1932. An overwet June was of major importance in 1911, 1929, 1932, and 1933. Insufficient soil moisture in April dominated the estimate in 1918, 1921, and 1925, whereas an overwet April contributed heavily to the low estimate in 1924.

If it is assumed that the basic yield in the early years is equal to the minimum of the quadratic fit, the basic yield would have been 0.93 tonnes per hectare for 1892 to 1942. If this were true, then years 1921, 1932, and 1933 would indicate complete crop failure. If crops in the Southwest Ukraine were really that bad in those years, there might be some mention of it in Ukrainian chronicles, but time and finances precluded any search for such information.

The net result of the analysis of the Southwest Ukraine is that weather accounts for about 15 percent of the variation of the winter wheat yield and that--although there are distinct oscillations in yield due to weather--there are no discernible periodic variations. The weak persistence suggests that bad years and good years might come in series, but there is little predictive value in the persistence. There is a hint in Fig. 8 that the decades between 1910 and 1940 had more variable weather conditions than the decades preceding

and following, but, as shown in Table 5, the crop failures can arise for a variety of causes. Only by defining annual patterns of weather events is it possible to relate crop variation with weather variation. The empirical orthogonal functions provide a partial answer to the problem of defining patterns, but we believe that a more careful choice of input parameters to a multivariate linear approach could sharpen the results considerably. With larger samples, it may be possible to derive a sequential approach--a successive stratification. For example, plants killed in a winter freeze cannot contribute to a late summer harvest, but in a strictly correlative approach data from years with winter kill dilute correlations of years with good winter survival. If such data could be discarded or modified before considering subsequent events, better correlations might be found. We do not believe that normal correlation techniques can provide the optimum approach, but unless large samples are available, successive stratifications are not possible.

III. OTHER REGIONS

SOUTH UKRAINE

The South Ukraine extends from Moldavia to the Crimean peninsula and from the coast of the Black Sea inland about 200 km. According to the Grigor'yev-Budyko classification, it is subhumid with warm summers and mild winters. Odessa--which is the key station for this area--has a little over one-half the annual precipitation of Kiev, and the annual temperature is about 2.5°C warmer than Kiev.

Instead of computing the soil moisture variable, we decided to use precipitation at Odessa as the moisture variable. There were two reasons for this decision: (1) the area is smaller and more homogeneous than the Southwest Ukraine, and (2) we wished to find out whether using precipitation directly would give acceptable results. We opted to retain the prior fall and winter temperatures and chose to use the average precipitation from August through March as a measure of soil moisture in the spring. We retained March temperature and added temperature and precipitation for April through July to the list of variables.

The variables used for the South Ukraine are:

T _N	Mean November temperature
T _W	Lowest mean monthly temperature in Dec., Jan., and Feb.
T _{Mr}	Mean March temperature
T _{Ap}	Mean April temperature
T _{My}	Mean May temperature
T _{Jn}	Mean June temperature
T _{Jy}	Mean July temperature
P _W	Average monthly winter precipitation, August-March
P _{Ap}	Total April precipitation
P _{My}	Total May precipitation
P _{Jn}	Total June precipitation
P _{Jy}	Total July precipitation

Empirical orthogonal functions were used to convert to 12 new variables in the same manner in which the variables were treated for the Southwest Ukraine. Of the 12 new variables, the four with the highest correlation with the yield deviation from the trend were chosen as predictors for yield deviation. The resulting formula is

$$\hat{y} = 0.0614x_{i6} + 0.0329x_{i7} - 0.1204x_{i10} + 0.0694x_{i9} \quad (9)$$

where the x_{ik} 's are numbered in descending order of their contribution to the total variance of the original independent variables. It should be noted that, although they contributed little to the overall variance of the original variables, eigenvectors 9 and 10 correlated highly with wheat yield deviation. They thus represent rare, but apparently important, deviations of the weather.

Converting Eq. (9) back to the original variables by means of the eigenvectors yields

$$\begin{aligned} \hat{y} = & -0.0105 \delta T_N + 0.0439 \delta T_W + 0.0472 \delta T_{Mr} - 0.0909 \delta T_{Ap} + 0.0003 \delta T_{My} \\ & - 0.1076 \delta T_{Jn} + 0.0391 \delta T_{Jy} + 0.0026 \delta P_W - 0.0059 \delta P_{Ap} \quad (10) \\ & + 0.0016 \delta P_{My} - 0.0020 \delta P_{Jn} + 0.0017 \delta P_{Jy} \end{aligned}$$

where the δ indicates the deviation from the 1955-1973 mean value. In general, the deviations from the mean of the precipitation are about one order of magnitude greater than the deviations from the mean of the temperature variables. If the precipitation coefficients in Eq. (10) are multiplied by 10, it is possible to make a rough ranking of the importance of each individual variable, as shown in Table 6. Obviously, the May and November variables have little effect, and the precipitation variables have less weight than the temperature variables.

Table 6
RANKING OF BASIC WEATHER VARIABLES

Variable	T _N	T _W	T _{Mr}	T _{Ap}	T _{My}	T _{Jn}	T _{Jy}	P _W	P _{Ap}	P _{My}	P _{Jn}	P _{Jy}
Rank	10	4	3	2	12	1	5	8	7	11	6	9

Table 7 shows the contributions of the 12 basic variables to the final estimate of the yield deviation for seven of the worst years in the series. From this table it appears that the data from the months of May and July have little effect. Cold winters and warm, wet weather in June seem to be the predominant contributors to poor yields. It is of interest to compare the patterns of the individual EOF's to the pattern of effects noted in Table 7. Since a positive value of the terms in Eq. (9) represent contributions to a good yield, a positive deviation is good with terms of a positive sign, and a negative deviation is good when the term has a negative sign. Table 8 compares the final result with each of the individual EOF's, taking only the eight highest ranked contributions of the initial variables to the EOF.

Figure 10 shows the estimated yield deviation in the South Ukraine for the years 1882 to 1935 and 1944 to 1973. As in the case of the Southwest Ukraine, the years of World War II interrupted the weather sequence. The solid line--as in Fig. 8--is a five-point smoothing function. A comparison of Figs. 8 and 10 suggests that the decades of the 20s and 30s had, in general, lower yields than earlier or later in the century. The details of the oscillations, however, show marked difference. The year 1893 was bad in the Southwest Ukraine, but fairly good in the South Ukraine; 1901 was bad in the South Ukraine, but fairly good in the Southwest Ukraine. In the recent data, 1970 was good in the South Ukraine and bad in the Southwest Ukraine. No single EOF matches the final equation, but it is possible to see how the weather patterns are reflected in the EOF's.

POOR CROP YIELD YEARS IN THE SOUTH UKRAINE

Table 7

Year	δT_N	δT_W	δT_{Mr}	δT_{Ap}	δT_{My}	δT_{Jn}	δT_{Jy}	δP_W	δP_{Ap}	δP_{My}	δP_{Jn}	δP_{Jy}	Total
1901	0.021	-0.070	0.076	-0.036	0.000	-0.451	-0.043	-0.017	-0.142	-0.034	-0.102	-0.004	-0.72
1917	0.008	-0.171	-0.066	-0.018	0.000	-0.086	-0.027	-0.000	0.070	-0.021	-0.122	-0.030	-0.46
1924	-0.060	-0.259	-0.094	-0.073	0.000	-0.441	0.000	-0.045	-0.130	-0.031	-0.030	-0.038	-0.99
1926	-0.012	-0.013	-0.425	-0.054	0.000	-0.075	0.035	-0.037	-0.012	-0.008	-0.272	0.001	-0.49
1929	-0.015	-0.435	-0.212	0.400	0.000	-0.065	0.000	-0.038	-0.060	-0.016	0.034	-0.045	-0.45
1932	0.034	-0.241	-0.217	0.009	0.000	-0.011	0.039	-0.032	-0.030	0.006	-0.114	-0.013	-0.57
1935	-0.012	-0.193	-0.024	-0.027	0.000	-0.280	-0.008	-0.022	-0.006	-0.038	-0.037	-0.047	-0.69

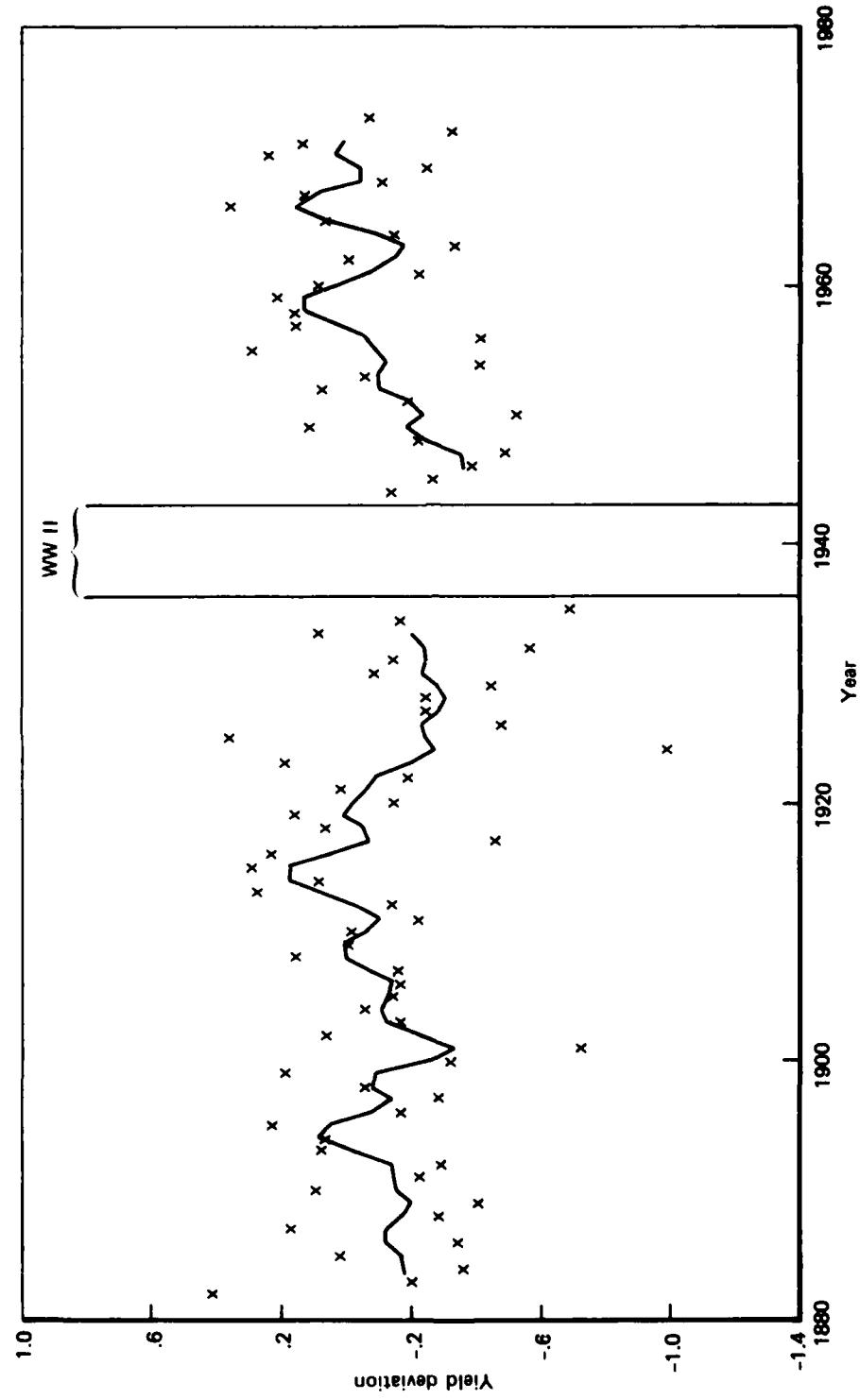


Fig. 10—Yield deviation due to weather factors, Odessa

Table 8

COMPARISON OF WEATHER PATTERN FOR GOOD YIELD OF THE
CHOSEN EOF'S WITH THE FINAL COMBINATION

Month	Final Result	χ_6	χ_7	χ_9	χ_{10}
Nov	-- ^a	--	Cool	Cool	--
Winter	Warm, wet	Warm, dry	Warm, wet	Warm, wet	Cool
Mar	Warm	Warm	Cool	Cool	Warm
Apr	Cool, dry	Warm, dry	Cool	Cool	Cool, dry
May	--, --	--, --	Cool	--, --	Warm, wet
June	Cool, dry	Cool, dry	Dry	Cool, dry	Cool
July	Warm	Warm	Dry	--, --	Warm

^aA dash means there was essentially no contribution to the EOF.

A time series analysis for the South Ukraine showed insignificant trends, persistence, and periods. This is similar to the result for the Southwest Ukraine except that the South Ukraine showed no persistence and the Southwest Ukraine showed weak persistence. In neither case is there any suggestion of a prediction of crop yield a year in advance *unless there are good predictions of the weather.*

KAZAKHSTAN AND WEST SIBERIA

The large wheat-growing region east of the Ural Mountains extends roughly from 60°E to 90°E and from 50°N to 55°N. The winters are too severe for winter wheat; therefore, only spring wheat is grown in this region. The area is much drier than the Ukraine, with only 200 to 300 mm of precipitation annually. According to the Grigor'yev-Budyko classification, it is subhumid, with warm summers and cold, dry winters. Although we have no definite information on the timing of spring wheat production in the area under consideration, a report by Baier (1977) on Canadian spring wheat suggests that, in these latitudes, planting should occur in May and harvesting in September.

To represent this area and this form of wheat culture, we used the average yields of West Siberia and Kazakhstan. The weather data were an average of the temperature and precipitation for Barnaul ($53^{\circ}20'N$, $83^{\circ}42'E$) and Omsk ($54^{\circ}56'N$, $73^{\circ}24'W$). Since the wheat is not planted until after the spring thaw, we did not use the November and winter temperatures in the analysis. With this exception, the variables used were the same as those used for the South Ukraine.

The orthogonal function analysis produced three EOF's which explained 91 percent of the variance of the original 10 variables for the period 1955 to 1973 inclusive and correlated highly with the yield. In terms of the transformed variables, the yield deviation is given by

$$\hat{y}_i = 0.0118x_{i4} - 0.0070x_{i2} + 0.0029x_{i1} \quad (11)$$

The multiple correlation coefficient is 0.85, and the equation accounts for 72 percent of the variance of the deviations from the trend in the dependent data. The breakdown of the total variance of the spring wheat yield in the region is shown in Table 9.

Table 9
DISTRIBUTION OF VARIANCE OF WHEAT YIELD
IN KAZAKHSTAN-WESTERN SIBERIA,
1955-1977
(Tonnes per hectare)

Cause of Variance	Variance	Percent of Total
All causes	0.120	100
Due to trend	0.044	36.7
Due to weather	0.055	45.8
Residual	0.021	17.5

It is noteworthy that in this area weather accounts for a greater fraction of the variance than the trend. It is possible that a quadratic trend may have shown a slightly greater fraction of the

variance due to trend, but this would most likely reduce the residual variance and still show that weather is the prime controller of yield. To determine the importance of each original variable to the yield deviation, the eigenvectors were used to transform Eq. (11) to the original variables:

$$\begin{aligned}\hat{y} = & -0.0017 \delta T_{Mr} - 0.0011 \delta T_{Ap} - 0.0007 \delta T_{My} - 0.0005 \delta T_{Jn} - 0.0008 \delta T_{Jy} \\ & + 0.0023 \delta P_W + 0.0121 \delta P_{Ap} + 0.0049 \delta P_{My} + 0.0042 \delta P_{Jn} + 0.0005 \delta P_{Jy}\end{aligned}\quad (12)$$

Note that below-average temperatures and above-average precipitation in all months lead to better yields. Note also that the effect of temperature is small compared to the effect of precipitation.

Figure 11 shows the estimated yield deviation for this area from 1922 to 1973. The solid line--as in Figs. 8 and 10--is a five-point smoothing designed to eliminate short-period fluctuations. The most noticeable feature of Fig. 11 is the large year-to-year fluctuation of yield deviation. Table 10 is a breakdown of the effect of each of the original variables for the years 1955 and 1956. These years were chosen because the estimated yield deviation changed from -0.31 to +0.30 between 1955 and 1956. The actual yield deviations went from -0.30 in 1955 to +0.48 in 1956. The difference between the two years is the precipitation in April, May, and June. The key to spring wheat culture in this area east of the Urals is precipitation in the late spring and early summer. If the rains fail, the wheat crop fails.

The time-series analysis of the data shown in Fig. 11 strongly suggests a cycle with a period of about two years. The one-year lag autocorrelation coefficient is -0.22. This is not significantly different from zero at the five percent level, but the fact that it is negative does suggest an alternation of the estimated yield. The spectral analysis showed a peak of 0.126 (tonnes per hectare)² at two years--the shortest period resolvable by the data. This peak was

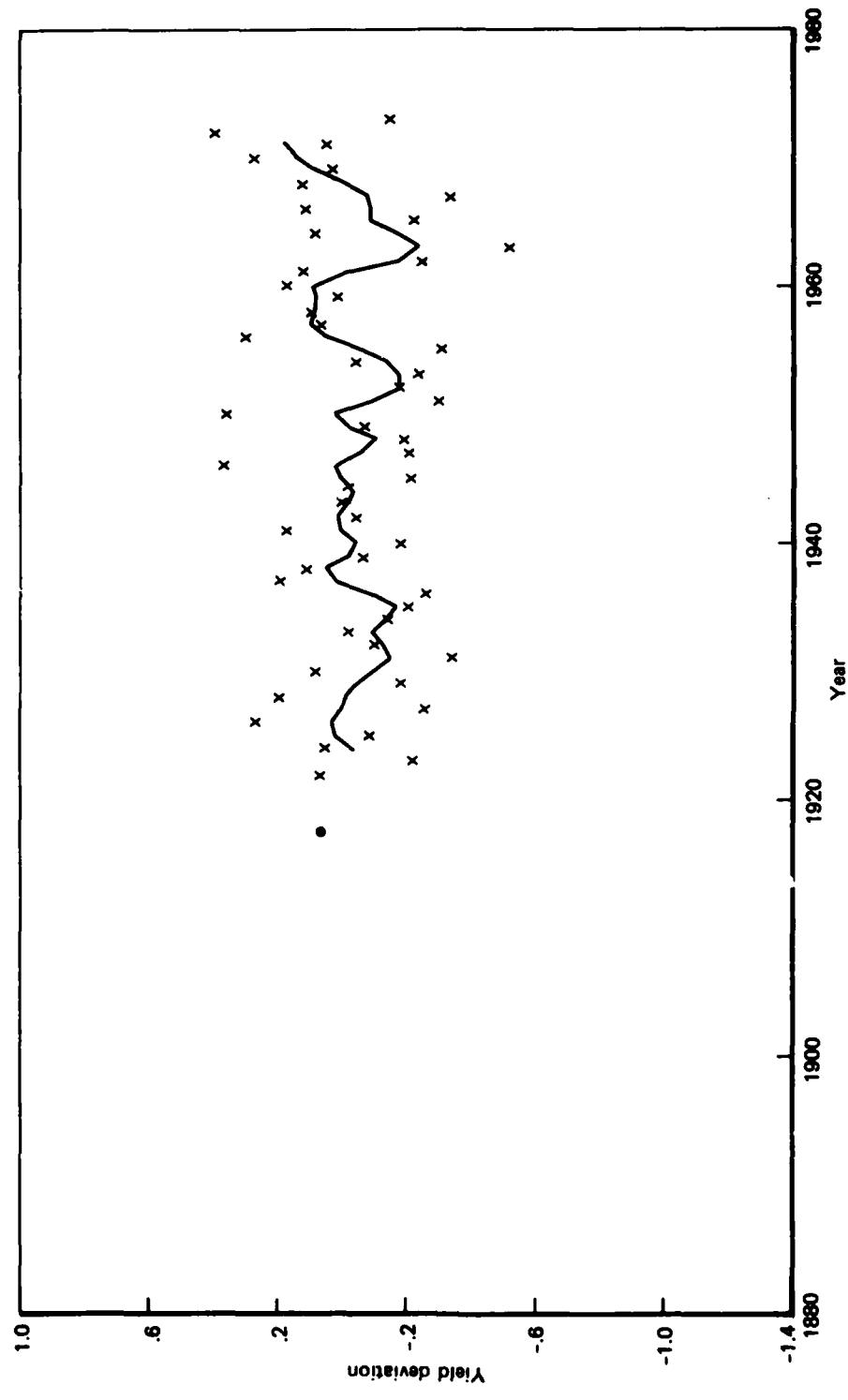


Fig. 11 — Yield deviation due to weather factors, Omsk-Barnaul

Table 10
COMPARISON OF TWO CONSECUTIVE YEARS

Year	Contribution of Each Original Variable to Yield Deviation										
	T _{Mr}	T _{Ap}	T _{My}	T _{Jn}	T _{Jy}	P _W	P _{Ap}	P _{My}	P _{Jn}	P _{Jy}	Total
1955	0.0039	0.0012	-0.0020	-0.0017	0.0000	-0.0053	-0.0726	-0.0220	-0.2037	-0.0047	-0.31
1956	0.0043	-0.0007	-0.0007	0.0013	-0.0004	-0.0207	0.1271	0.0550	0.1323	-0.0024	0.30

significant at the one percent level. Since 18 frequency bands were computed, the expectation of having one band with a variance estimate this high is small. The Kendall turning point test (Kendall, 1966) showed a 95 percent probability of a nonrandom distribution. This test is particularly good for high-frequency, short-period oscillations. It should be borne in mind that the yield estimates are in reality complex combinations of weather elements, even though they are expressed in tonnes per hectare. There is considerable evidence (e.g., Landsberg et al., 1963) that cycles with periods between 23 and 25 months exist in the atmosphere. With the evidence at hand, we feel that an alternation of good and bad crop years in the Kazakhstan-West Siberia spring wheat region might be a persistent feature of the climate. This might have some predictive validity.

IV. YIELD VARIABILITY VERSUS WEATHER VARIABILITY

Figure 12, a sketch map of the major wheat regions of the USSR, shows the Grigor'yev-Budyko climate classifications. The regions analyzed in this report are shaded. The two areas of the Ukraine--Southwest and South--account for about one-fourth of the winter wheat production. Most of the rest is produced in regions immediately to the north and east of the areas analyzed. The areas to the north have climates similar to the Southwest Ukraine, whereas the areas to the east have climates similar to the South Ukraine. Over half the spring wheat is produced in the Kazakhstan-West Siberia region. Most of the rest of the spring wheat is produced in the Volga and Ural regions, which have similar climates. There are small amounts of spring wheat grown in European USSR and small amounts of winter wheat grown in the south of the Volga and Kazakhstan regions, but it is safe to generalize by saying that most of the winter wheat is grown in the southern part of European USSR and most of the spring wheat is grown in the western part of Asiatic USSR.

Spring wheat--although its yield per hectare is only about half that of winter wheat--accounts for 50 to 60 percent of the Soviet wheat production in most years. The predominance of the spring wheat in the total production figures is the result of the large regions devoted to its culture. Two to three times more area is planted in spring wheat than in winter wheat.

Because spring wheat generally provides the bulk of the Soviet wheat crop, its success or failure has a large bearing on the total Soviet wheat production. Moreover, spring wheat is grown in the colder, drier areas of the Soviet Union and is therefore more subject to the vagaries of the weather, as indicated by the high percentage of the variance of the Kazakhstan-West Siberia yield that can be attributed to weather. The standard error about the trend lines for the three areas studied are

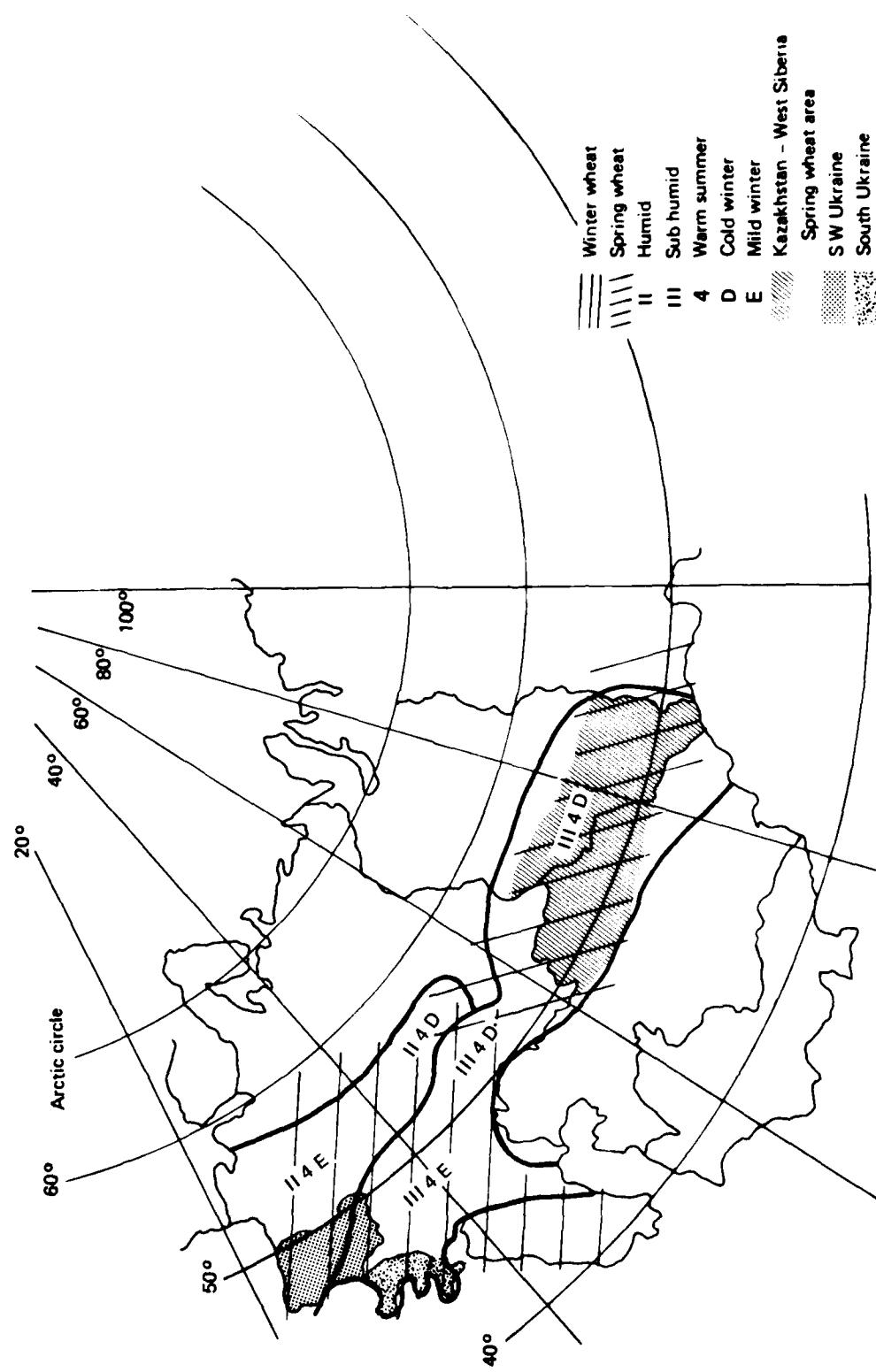


Fig. 12—Wheat region, climate regions, and areas studied

Southwest Ukraine	0.232
South Ukraine	0.276
Kazakhstan-West Siberia	0.276

The variations about the trend lines are very similar. If, however, we take the ratio of these standard errors to the value of the trend line at some fixed time--say, 1973--this ratio is

Southwest Ukraine	0.080
South Ukraine	0.089
Kazakhstan-West Siberia	0.256

Thus the ratio of the standard error to an expected value--called the coefficient of variation--is much greater for the more marginal areas of spring wheat than it is for the well-watered areas of winter wheat.

Kogan (1977) shows a plot of the coefficient of variations of the yield of grain crops for 19 experimental farms and 16 production organizations as a function of the normal precipitation in the January-September period of the year. The data show an inverse relationship, with high values of the coefficient of variation where the precipitation was low, and low values where the precipitation for the period was high. The January-September precipitation for the years 1955-1973 was computed for the key stations in each of the areas studied as:

Southwest Ukraine	Kiev	484 mm
South Ukraine	Odessa	355 mm
Kazakhstan-West Siberia	Omsk-Barnaul	310 mm

The coefficient of variability for wheat yield as estimated above for Kiev and Omsk-Barnaul fits closely to Kogan's data, but Odessa rainfall suggests more crop variability than is observed. This discrepancy might arise because the areas inland from Odessa in the South Ukraine get more summer rainfall than Odessa (Lydolph, 1977).

Not all of the regions of the USSR are affected simultaneously by adverse weather. Data for the entire wheat crop of the Soviet Union from 1955 through 1974 (ERS, 1977) were fitted with a trend line, and the variance about the trend was computed to be 0.176 tonnes per hectare. This is considerably less than the values obtained for any of the three regions studied and indicates a compensation among the regions. Of the 20 years of record, only 1963 showed substantial negative deviation from the trend in the three regions studied, and that year was the worst year in the period of record for the entire USSR. In 1966 and 1971, all of the three regions studied showed considerably better than normal yields, and the total for the USSR was well above normal. The best year for the entire USSR in the 1955-1974 period was 1973. Although the regions considered in this study were normal or slightly above normal, it was not a banner year for any of them. This suggests that some of the areas that were not considered in this study must have had very good crops in 1973.

There is no doubt that the patterns of temperature and rainfall during the growing season have a marked effect on the yield of wheat. There is also no doubt that improved technology--particularly the use of fertilizer--has increased the yield over the past 10 to 20 years. There is, however, no indication that improved technology has counteracted the effect of weather. The year-to-year variability appears to be as great in the early 1970s as it was in the late 1950s. Kogan (1977), who analyzed a much longer period of crop yield data, suggests that the variability may be increasing. Until such time as the trend reaches a point where the large negative deviations from the trend can be tolerated and the positive deviations stockpiled for future use, the variability of the Russian weather will result in years when the Soviets will need to look outside their own country for sufficient quantities of wheat.

The trend lines we have fitted for analytical purposes cannot be extended into the indefinite future. In the humid, warm summer, mild winter climates of Illinois and Indiana, Thompson (1969) reported the trend in yield at about 37 bushels per acre by 1968, with some

indication of leveling off. This converts to about 2.5 tonnes per hectare. Our trend estimates for the South Ukraine exceeded this value by 1970. There are some discrepancies in the way yields are reported in the two countries, but it is apparent that the Soviets are pushing their technology to the limits. We cannot state what the yield might be when technology has maximized the output of wheat from a hectare of land, but the weather will always cause major variation about the ~~te~~ logically established mean.

These rough figures suggest that the weather might have been more favorable for wheat production during the period of record used for developing the estimating procedures than they were in earlier years. The excellent yields of 1970, 1971, and 1973 represent a combination of improved technology and excellent weather conditions which could be expected only about two percent of the time with a climatic regime such as we have had over the last century.

V. SOME SCENARIOS FOR THE FUTURE

Climate is defined in the *Glossary of Meteorology* (Huschke, 1959) as

"The synthesis of the weather" (C. S. Durst); the long term manifestations of weather, however they may be expressed.

For our purposes, the climate is expressed by yield deviation estimates, as shown in Figs. 8, 10, and 11. These three figures show the synthesized effect of the weather on wheat yields for each year, and the statistics of these estimates represent the important features of the climate for wheat culture. The time series analysis of these values showed no significant trend, weak persistence at Kiev, no persistence at Odessa or Omsk-Barnaul, and no cyclic behavior except a possible two-year cycle at Omsk-Barnaul. Despite the lack of significant cycles, it is apparent from the figures that there are oscillations in the weather that cause runs of good and bad years.

For the first scenario we assume that there will be no marked change in the climate and that the data from the 1882 to 1973 period represent the climate. As a measure of a sequence of bad years, we will use the five-year smoothed values shown on the figures. Recall that the yield deviation estimates were based on trend lines from the years 1955 to 1973 so that the yield deviations average to zero through this period. There is, however, no reason to expect that the weather was always so benign. Earlier years at Kiev and Odessa do show larger negative yield values than the recent decades.

The distribution of the values of the five-year weighted running means is shown in Fig. 13. These values are not serially independent, but if we ask only that a given five-year period have a deviation from the trend of a given amount, that value can be read from the figure. For both Ukrainian areas the record extends back to

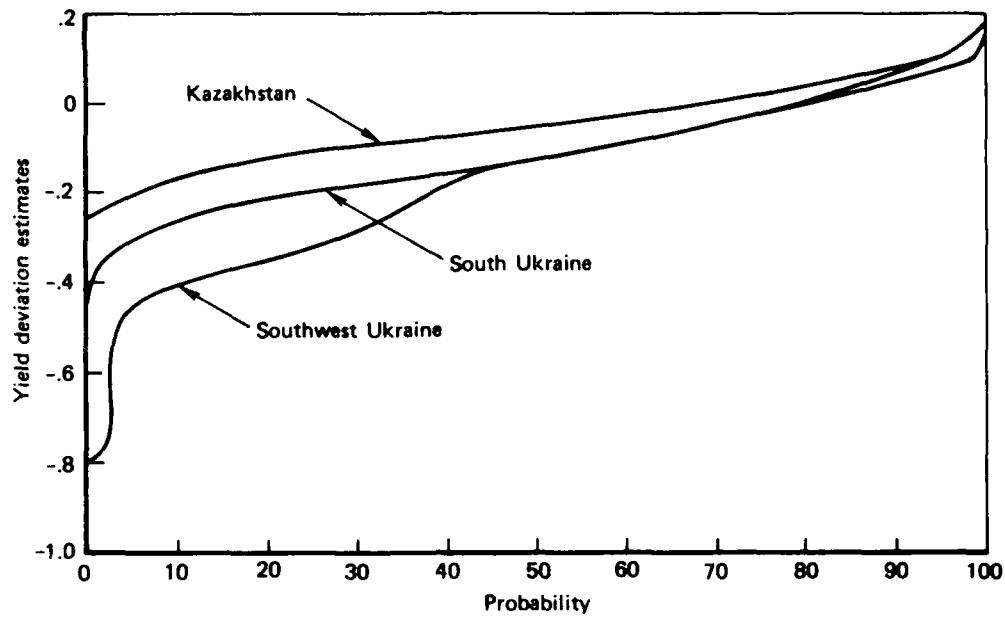


Fig. 13 — Distribution of yield deviation estimates

1882, and both show about an 80 percent probability of having negative yield deviations. The years 1924 through 1932 were apparently very bad crop years in the Ukraine, and this period weighs heavily on the distribution. The data for Kazakhstan-West Siberia go back only to 1922. The area did, however, have a bad period from 1930 to 1936, which was not included in the development data, and therefore negative yield deviations can be expected almost 70 percent of the time.

It is not possible to derive hard statistics for the wheat yield of the entire country from our three samples. The spatial variations of the weather in any given year can benefit one area and harm another. There are periods, however, when all three of the areas had adverse weather patterns. Smoothed estimated yield deviations for all three areas were available for the years 1924 to 1933 and 1947 to 1971. Of these 35 years, there were eight years in which the estimated yield deviations for all areas were simultaneously in the lower half of the distributions shown in Fig. 13. We conclude, therefore, that with no change in climate, the Soviet Union will

experience periods of adverse weather in at least one year in four that will reduce their entire wheat crop below the level which is technologically achievable.

It is unlikely that there will be any changes in the climate in the next 20 years or so that will be detectable when compared with the normal weather oscillations. There are, however, factors which could conceivably alter the global climate. First is a long-term cooling trend which is apparently brought about by long-period cyclic variations in the general circulation. This trend has been detected in Northern Hemisphere mean temperatures since the mid-1940s and is somewhat supported by isotopic analysis of Greenland ice cores (Gribbin and Lamb, 1978). Another factor is the potential for global warming by the increase in atmospheric carbon dioxide. It is not possible to make any precise relation between these trends and the weather patterns of the wheat-growing regions of Russia, but we can make some rough inference of the effect of either global warming or global cooling.

The second scenario is based on the thesis that carbon dioxide will raise the global temperatures and decrease the pole-to-equator temperature gradient (Manabe and Wetherald; 1980, 1975). The decrease in the pole-to-equator thermal gradient should cause a weakening of cyclonic activity and an increase in the monsoonal character of the global circulation. By reconstructing the precipitation patterns of the so-called *Climatic Optimum* which occurred about 7000 years ago, Kellogg (1978) suggests that the monsoonal circulation from the Mediterranean, Black, and Caspian Seas would bring increased moisture to the Russian wheat belt. The increased moisture would be . . . in the regions which are now classified as subhumid, and the warmer temperatures would minimize the amount of winter freeze. Warmer summer temperatures and more rainfall in the humid regions might be detrimental to the ripening process. On balance, a warming trend would seem to favor increased Soviet wheat production. The vast areas of Kazakhstan and West Siberia could be much more favorable. There is a possibility that

winter wheat could be introduced into these areas and the yield raised considerably by milder winters and more precipitation.

In addition to improving conditions in the Kazakhstan-West Siberia region, it is possible that warmer temperatures in higher latitudes would open up new lands for wheat production. An earlier Rand study (Rapp, unpublished) showed that Soviet agriculture was severely limited in area by the length of growing season and the availability of sufficient precipitation. Even a small increase in mean temperature could greatly extend the growing season in many parts of the USSR. The extent to which this lengthened growing season could be utilized would depend on the available moisture. If the postulated monsoonal circulation extended north and east from Kazakhstan, the potential wheat-growing region might be increased enormously.

The third scenario--a continued cooling trend--could be disastrous for Soviet agriculture. Overall global cooling would shift Arctic-like climate to lower latitudes. Cyclonic activity would probably increase, but storm tracks would tend to move southward and reduce the precipitation in the present wheat-producing regions. It is possible that some areas of southern Kazakhstan that at present are too dry and hot for wheat production could increase their contribution to the wheat crop, but the net effect on the area available for production would be a decrease. Even a small decrease in mean global temperature could so shorten the growing season that millions of hectares now in production would no longer be usable.

Probably the best estimate for the effect of climate on Soviet wheat production in the next 20 years is that it will profit--and suffer--from the same kind of weather changes that it has felt during the last century. Although technological improvements should lead to increased yields, such increases have a limit. Interannual variations in weather patterns will continue to cause rather large variations in yield. With no climatic changes, there are no more areas in the Soviet Union that can be opened to wheat culture. Any increase in demand will need to be met by improved yield from the present acreage.

SUMMARY

It is evident that the time sequence of precipitation and temperature during the growing season of wheat has a marked effect on yield. The estimating equations developed in this study capture only the gross features of the effective weather patterns because they were limited to monthly data and used data from only one or two weather stations to represent large areas. Nevertheless, the equations do capture the temporal patterns which affect wheat yield. The application of the estimating equations to historical weather data introduces additional error into the estimates. The estimated yield deviations do, however, provide an index of how the weather patterns in the years of historical weather data would affect the crops.

In attempting to construct scenarios for the future, there is no hard information on either the possible trend of global temperatures or the manner in which such trends would affect the weather in the Soviet Union. The proposed scenarios are, therefore, merely guesses based on fragmentary information. The most logical assumption for the next 20 or 30 years is that the kind of nonperiodic oscillating seen over the last century will continue. In a previous study (Rapp, unpublished) of the Soviet approach to climate modification it was concluded that Soviet climate modification plans were not pushed more vigorously because the hypothesized outcome of the proposed actions was too uncertain to risk the experiment.

Given the continuation of the climatic oscillations of the past century, the USSR will continue to have recurrent grain shortages. If technology and management improvements could raise the yields of all wheat-producing regions to the level of the experimental farms studied by Kogan (1977), the USSR might become self-sufficient in wheat production. It seems unlikely, however, that the Soviets could--or would--choose to make the tremendous investment of time, money, and production facilities to achieve this goal.

If the worldwide warming scenario were to occur, it *might* benefit Soviet wheat production. If the cooling scenario were to occur, it *might* be disastrous for Soviet wheat production. The more

likely event is that the Soviets will continue to have wheat crops insufficient for their needs and that about one year in 20 will produce weather patterns that will result in a crop with a disastrously low yield.

A question which needs to be addressed is: What are the limits of technological improvement?

Appendix
PROCEDURES

The methodology consists of ten separate procedures, nine of which are computer procedures. These computer procedures include FORTRAN programs and data handling and statistical packages. Table 11 shows all the procedures with the input data required and the data generated.

This appendix includes a description of each of the procedures. Several procedures require changes for using other variables; these changes are noted in the description of the individual procedure.

Procedures 1 through 5 will normally be performed for the complete set of data available. The yield data available for the area corresponding to the weather station may be for a shorter time period than the weather data. Procedures 6 through 8 will be performed using weather data for the time period corresponding to the yield data. Procedures 9 and 10 will be used on whatever continuous series of data are available.

Following are descriptions of each of the procedures.

PROCEDURES 1 THROUGH 4

This methodology uses the World Monthly Surface Climatology* data for the basic weather data. A data-handling procedure (Procedure 1) extracts the weather data for the stations of interest.

The trend analysis for the yield data was done on a TI 58 desk computer. Simple programs were used to determine the coefficients of linear and quadratic forms of yield versus time.

$$\hat{Y} = a + b (\text{year} - 1955)$$

$$\hat{Y} = a + b (\text{year} - 1955) + c (\text{year} - 1955)^2$$

*These data, descriptions, and formats are available from Wilbur M. L. Spanler, Computing Facility, National Center for Atmospheric Research (NCAR), Boulder, Colorado 80302.

Table 11
METHODOLOGY PROCEDURES

PROCEDURE	INPUT DATA	DATA GENERATED
1. Weather data retrieval	World weather records	Station weather records
2. Yield deviation determination		Yield deviation
3. Temperature and precipitation extraction program	Station weather records	Temperature Precipitation
4. Statistics	Temperature or precipitation	
5. Soil moisture calculation	Temperature Precipitation	Soil moisture Deviation of soil moisture
6. Variable creation	Temperature	Variable deviation from mean
7. Eigenvector	Deviation of soil moisture	Variable deviation from mean Eigenvalues Q's
8. Correlation	Q's with yield deviation added	
9. Yield deviation determination (by equation)	Temperature Deviation of soil moisture Means	Variable deviation from mean Q's Yield deviation
10. Time series	Eigenvectors	Station name Number of lags Yield deviation

The yield, Y , minus the trend \hat{Y} or \tilde{Y} became the basic independent variable for further computation. The choice of a linear or quadratic trend was made on the basis of the reduction in the RMS value of $y = (Y - \hat{Y})$ or $(Y - \tilde{Y})$. If the quadratic yielded a major reduction of the RMS value over the linear, it was chosen to represent the trend. If a minimum occurred within the 1955 to 1973 period, the trend was assumed to have that minimum from 1955 to the year the minimum occurred.

A FORTRAN program (Procedure 3) converts the weather data as necessary and writes data files containing the temperature and precipitation. A statistical package, SPSS,* (Procedure 4) provides descriptive statistics (means, standard error, standard deviation, variance, kurtosis, skewness, range, maximum, minimum) for the data input.

The soil moisture bookkeeping system of Thornethwaite and Mather (1957) was fitted to equations and automated for machine computation. The basic evaporation equation is

$$PE = F(aT^b)$$

where PE is the potential evapotranspiration, F is a length of day factor dependent on latitude, and the constants a and b depend on the annual march of temperature. The water deficit in any month is

$$D_j = PE_j - P$$

where P is the monthly rainfall accumulation. The water retained in the soil during a dry period is

*Statistical Package for the Social Sciences (SPSS), Second Edition, McGraw-Hill Book Publishers, 1975.

$$M_{j+1} = M_o \exp \left[- \frac{c}{M_o} \sum_{j=1}^i D_j \right]$$

where M_o is the holding capacity of the soil and c is a constant expressing the fraction of water retained for a given water deficit.

The value $j = 0$ at the first month in which D_j is positive, and M_i is computed for all months when D_j is positive. For months when D_j is negative, $M_i = M_o$. The soil moisture excess is equal to $M_o - D_j$. M_o was chosen as 300 mm, and F was read for the middle day of each month from the Thornethwaite and Mather tables. By fitting these equations to the tables, a was chosen as 0.108, $b = 1.146$, $c = 1.012$. With these equations, the following program constructs a monthly soil water budget from the mean monthly temperatures and the monthly rainfall totals.

PROCEDURE 5

SOIL, a FORTRAN program, calculates the soil moisture and the deviation of soil moisture from 300 and writes data files containing the values. Figure 14 is a listing of the SOIL program.

All constants are set to their appropriate values initially, and the soil moisture (SOILM) and deviation of soil moisture (SOILD) arrays are set to -999.9 to remain default if there are missing temperature or precipitation data. The header record is read from the temperature and precipitation data files (FORTRAN units 15 and 16) and written on the soil moisture and soil moisture deviation data files (FORTRAN units 26 and 27). The year and the 12 months of temperature (TEMP(K)) and precipitation (PREC(K)) data are then read. Flags are set if there are missing temperature or precipitation data, and further calculations for that year are bypassed. If there are missing data, the SOILM and SOILD arrays are written (FORTRAN units 26 and 27) for that year, and the next year is set to begin in month 4 (April) with the soil moisture of the previous month, SOILM (3), set to 300.

```
//B9630PSO JOB (2954,050,061),'SOIL TABLES',CLASS=N
///* SAVED AS SOIL
// EXEC FORTCLG
//FORT.SYSIN DD *
      DIMENSION CAPA(12),SOILM(12),SOILD(12),TEMP(12),PREC(12)
      DIMENSION STANAM(3)
C
C***** SET CONSTANTS
C
      XLAMB =-3.373E-03
      ALPHA =0.108
      BETA =1.146
      CAPA( 1)= 22.5
      CAPA( 2)= 23.7
      CAPA( 3)= 30.6
      CAPA( 4)= 34.5
      CAPA( 5)= 39.6
      CAPA( 6)= 40.2
      CAPA( 7)= 40.5
      CAPA( 8)= 37.2
      CAPA( 9)= 31.5
      CAPA(10)= 27.6
      CAPA(11)= 22.8
      CAPA(12)= 21.3
C
      ISTART =1
      PREM=300.
      MISST=0
      MISSP=0
      IYR=1900
      KYR=1
C
      DO 100 I=1,12
      SOILD(I)=-999.9
100  SOILM(I)=-999.9
C
C
C
      READ (15,1001) (STANAM(I),I=1,3),IWMO
      READ (16,1001) (STANAM(I),I=1,3),IWMO
      WRITE (26,2000) (STANAM(I),I=1,3),IWMO
      WRITE (27,3000) (STANAM(I),I=1,3),IWMO
C
      50 CONTINUE
C
      READ (15,1002,END=9000) NYR,(TEMP(I),I=1,12)
      READ (16,1002,END=9000) NYR,(PREC(I),I=1,12)
      IF (NYR .GT. 2000) GO TO 9000
      IF (KYR .NE. 1 .AND. NYR-IYR .GT. 1) ISTART=4
      IF (KYR .NE. 1 .AND. NYR-IYR .GT. 1) SOILM(3)=300.
C
      DO 200 K=ISTART,12
      IF (TEMP(K) .EQ. 99. .OR. TEMP(K) .EQ. -99.9) MISST=1
      IF (PREC(K) .EQ. 20000. .OR. PREC(K) .EQ. -999.9) MISSP=1
      IF (MISST .EQ. 1 .OR. MISSP .EQ. 1) GO TO 210
      IF (TEMP(K) .LE. 0.0) GO TO 110
      DEE = (CAPA(K)*ALPHA*TEMP(K)**BETA) - PREC(K)
      GO TO 115
110  CONTINUE
      DEE = -PREC(K)
```

Fig. 14 — SOIL

```
115 CONTINUE
IF (K .GT. 1) GO TO 120
IF (DEE .LE. 0.0) SOILM(K)=PREM - DEE
IF (DEE .GT. 0.0) SOILM(K)=PREM*EXP(XLAMB*DEE)
GO TO 180
120 CONTINUE
IF (DEE .LE. 0.0) SOILM(K)=SOILM(K-1) - DEE
IF (DEE .GT. 0.0) SOILM(K)=SOILM(K-1)*EXP(XLAMB*DEE)
180 CONTINUE
SOILD(K) = SOILM(K) - 300.
IF (SOILM(K) .GT. 300.) SOILM(K)=300.
200 CONTINUE
210 CONTINUE
WRITE (26,1002) NYR,(SOILM(I),I=1,12)
WRITE (27,1002) NYR,(SOILD(I),I=1,12)
KYR=KYR+ 1
IYR=NYR
ISTART=1
PREM=SOILM(12)
DO 250 I=1,12
SOILD(I)=-999.9
250 SOILM(I)=-999.9
IF (MISST .EQ. 1 .OR. MISSP .EQ. 1) ISTART=4
IF (MISST .EQ. 1 .OR. MISSP .EQ. 1) SOILM(3)=300.
MISST = 0
MISSP = 0
GO TO 50
C
9000 CONTINUE
C
***** FORMATS
C
1001 FORMAT (5X,3A4,8X,I8//)
1002 FORMAT (3X,I4,12F9.1)
2000 FORMAT (5X,3A4,4X,'WMO#',I8/
     1           /5X,'SOIL MOISTURE'/
     2           /3X,'YEAR',5X,'JAN',6X,'FEB',6X,'MAR',6X,'APR',
     3           6X,'MAY',6X,'JUN',6X,'JUL',6X,'AUG',6X,'SEP',
     4           6X,'OCT',6X,'NOV',6X,'DEC')
3000 FORMAT (5X,3A4,4X,'WMO#',I8/
     1           /5X,'SOIL MOISTURE DEVIATION FROM 300.0'/
     2           /3X,'YEAR',5X,'JAN',6X,'FEB',6X,'MAR',6X,'APR',
     3           6X,'MAY',6X,'JUN',6X,'JUL',6X,'AUG',6X,'SEP',
     4           6X,'OCT',6X,'NOV',6X,'DEC')
C
CONTINUE
END
//GO.FT15F001 DD UNIT=USER,DISP=SHR,DSN=B.B9630.A2954.TEMP.KIEV
//GO.FT16F001 DD UNIT=USER,DISP=SHR,DSN=B.B9630.A2954.PREC.KIEV
//GO.FT26F001 DD UNIT=USER,VOL=SER=USER52,DISP=(NEW,CATLG),
//           SPACE=(TRK,(1,1),RLSE),DCB=(RECFM=F,LRECL=115,BLKSIZE=115),
//           DSN=B.B9630.A2954.SOILM.KIEV
//GO.FT27F001 DD UNIT=USER,VOL=SER=USER52,DISP=(NEW,CATLG),
//           SPACE=(TRK,(1,1),RLSE),DCB=(RECFM=F,LRECL=115,BLKSIZE=115),
//           DSN=B.B9630.A2954.SOILD.KIEV
```

Fig. 14 — continued

If there are no missing data, the following calculations are performed:

```
TEMP(K) > 0 : DEE = [CAPA(K)*ALPHA*TEMP(K)**BETA] - PREC(K)
TEMP(K) ≤ 0 : DEE = PREC(K)
DEE ≤ 0 : SOILM(K) = SOILM(K - 1) - DEE
DEE > 0 : SOILM(K) = SOILM(K - 1)*EXP(XLAMB*DEE)
```

where K is the month index. If the calculation is for the first month of the year, SOILM(K - 1) = PREM = SOILM(12) of the previous year, or if this is the first year to be calculated, PREM = 300.

The deviation of soil moisture (SOILM) from 300 is then calculated, and if soil moisture (SOILM) is greater than 300, it is set equal to 300. The data are then written on the data files (FORTRAN units 26 and 27). Another year of data is then read from the temperature and precipitation files and calculations continue until either an end of file or a 10- or 30-year monthly average record (year = 2000) is encountered.

PROCEDURE 6

VARPGMAV, a FORTRAN program, determines the variables to be used in the calculation of the yield deviation, determines their means and the deviation from the mean, and writes the means and deviation from the mean on a data file. Figure 15 is a listing of the VARPGMAV program.

This version of the program determines 7 variables: T_N , T_W (lowest mean monthly temperature of December, January, and February), T_{Mr} , $|M_{Ap}|$, $|M_{My} + 40|$, T_{Jn} , $|M_{Jn} + 105|$. All of the variables are the deviation from the mean.

If other variables are to be determined, changes will be required to the dimension, read, write, and format statements and some calculations.

In this case, including T_N and T_W , it is necessary to begin the input data one year earlier than the desired output, i.e., if 1955 is the first year desired, 1954 must be first year of input.

```
//B9630VAR JOB (2954,050,061),'VARIABLES',CLASS=N
//***** SAVED AS VARPGMAV
// EXEC FORTCLG
//FORT.SYSIN DD *
      DIMENSION IYEAR(100),TNOV(100),TWIN(100),TMAR(100),
      1          TJUN(100),XMAP(100),XMMY(100),XMJN(100),
      2          XMAPA(100),XMMYA(100),XMJNA(100),STANAM(3),NVAL(7)
C
      READ (15,1001) (STANAM(I),I=1,3),IWMO
      READ (16,1001) (STANAM(I),I=1,3),IWMO
      READ (15,1000) TNOV(1),TDEC
      READ (16,1000) DUMMY
      I=1
C
      10 CONTINUE
C
      READ (15,1002,END=9000) IYEAR(I),TJAN,TFEB,TMAR(I),TJUN(I),
      1                      TNOV(I+1),TDEC
C
      TWIN(I) = AMIN1(TDEC,TJAN,TFEB)
      TDEC = TDEC
C
      READ (16,1003,END=9000) XMAP(I),XMMY(I),XMJN(I)
C
      I = I+1
      GO TO 10
      9000 NYR = I-1
C
      WRITE (6,2000) (STANAM(I),I=1,3),IWMO
C
      DO 100 I=1,NYR
      WRITE (6,2001) IYEAR(I),TNOV(I),TWIN(I),TMAR(I),XMAP(I),
      1                  XMMY(I),TJUN(I),XMJN(I)
C
      100 CONTINUE
C
      DO 160 I=1,NYR
      XMAPA(I) = ABS(XMAP(I))
      XMMY(I)=XMMY(I)+40
      XMMYA(I)=ABS(XMMY(I))
      XMJN(I)=XMJN(I)+105
      XMJNA(I)=ABS(XMJN(I))
      160 CONTINUE
C
      WRITE (6,2000) (STANAM(I),I=1,3),IWMO
C
      DO 115 I=1,NYR
      WRITE (6,2001) IYEAR(I),TNOV(I),TWIN(I),TMAR(I),XMAP(I),
      1                  XMMY(I),TJUN(I),XMJN(I)
C
      115 CONTINUE
C
      CALCULATE MEANS
C
      SET INITIAL VALUES
C
      SUMTN=0.0
      SUMTW=0.0
      SUMTM=0.0
```

Fig. 15 — VARPGMAV

```
SUMTJ=0.0
SUMSA=0.0
SUMSM=0.0
SUMSJ=0.0
DO 121 K=1,7
121 NVAL (K)=0
C   SUM VALUES
C
DO 120 I=1,NYR
SUMTN=SUMTN+TNOV(I)
NVAL(1)=NVAL(1)+1
SUMTW=SUMTW+TWIN(I)
NVAL(2)=NVAL(2)+1
SUMTM=SUMTM+TMAR(I)
NVAL(3)=NVAL(3)+1
SUMTJ=SUMTJ+TJUN(I)
NVAL(4)=NVAL(4)+1
IF(XMAPA(I).GT.800) GO TO 126
SUMSA=SUMSA+XMAPA(I)
NVAL(5)=NVAL(5)+1
126 IF (XMMYA(I).GT.800) GO TO 127
SUMSM=SUMSM+XMMYA(I)
NVAL(6)=NVAL(6)+1
127 IF(XMJNA(I).GT.800) GO TO 120
SUMSJ=SUMSJ+XMJNA(I)
NVAL(7)=NVAL(7)+1
120 CONTINUE
NVAL1=NVAL(1)
NVAL2=NVAL(2)
NVAL3=NVAL(3)
NVAL4=NVAL(4)
NVAL5=NVAL(5)
NVAL6=NVAL(6)
NVAL7=NVAL(7)
XMNTN=SUMTN/NVAL1
XMNTW=SUMTW/NVAL2
XMNTM=NVAL3/NVAL3
XMNTJ=SUMTJ/NVAL4
C
XMNSA=SUMSA/NVAL5
XMNSM=SUMSM/NVAL6
XMNSJ=SUMSJ/NVAL7
C
C   CALCULATE DEVIATION FROM MEANS
C
DO 140 I=1,NYR
TNOV(I)=TNOV(I)-XMNTN
TWIN(I)=TWIN(I)-XMNTW
TMAR(I)=TMAR(I)-XMNTM
TJUN(I)=TJUN(I)-XMNTJ
C
XMAPA(I)=XMAPA(I)-XMNSA
XMMYA(I)=XMMYA(I)-XMNSM
XMJNA(I)=XMJNA(I)-XMNSJ
140 CONTINUE
C
WRITE (6,2002)
WRITE (6,2003) XMNTN,XMNTW,XMNTM,XMNSA,XMNSM,XMNTJ,XMNSJ
WRITE (26,1999) (STANAM(I),I=1,3),IWMO
WRITE (26,2002)
WRITE (26,2003) XMNTN,XMNTW,XMNTM,XMNSA,XMNSM,XMNTJ,XMNSJ
```

Fig. 15 — continued

```
      WRITE (26,3000)
C
      DO 200 I=1,NYR
      WRITE (26,2001) IYEAR(I),TNOV(I),TWIN(I),TMAR(I),
      1           XMAPA(I),XMMYA(I),TJUN(I),XMJNA(I)
      200 CONTINUE
C
C***** FORMATS
C
      1000 FORMAT (97X,2F9.1)
      1001 FORMAT (5X,3A4,8X,18//)
      1002 FORMAT (3X,I4,3F9.1,18X,F9.1,36X,2F9.1)
      1003 FORMAT (34X,3F9.1)
      1999 FORMAT (5X,3A4,4X,'WMO#',I8)
      2000 FORMAT (1H1,5X,3A4,4X,'WMO#',I8/
      1           /5X,'VARIABLES'/
      2           /3X,'YEAR',5X,'TNOV',5X,'TWIN',5X,'TMAR',4X,'MDAPR',
      3           4X,'MDMAY',5X,'TJUN',4X,'MDJUN')
      2001 FORMAT (3X,I4,7F9.1)
      2002 FORMAT (//3X,'MEANS'/
      2           /4X,'TNOV',5X,'TWIN',5X,'TMAR',4X,'MDAPR',
      3           4X,'MDMAY',5X,'TJUN',4X,'MDJUN',4X,'***MOISTURE - ',
      4           'MEANS OF ABSOLUTE VALUES')
      2003 FORMAT (F8.1,6F9.1)
      3000 FORMAT (/)
      1           /5X,'VARIABLES - DEVIATION FROM MEAN (MOISTURE',
      2           ' ABSOLUTE VALUE)'/
      2           /3X,'YEAR',5X,'TNOV',5X,'TWIN',5X,'TMAR',4X,'MDAPR',
      3           4X,'MDMAY',5X,'TJUN',4X,'MDJUN')

C
      END
//GO.FT15F001 DD UNIT=USER,DISP=SHR,DSN=B.B9630.A2954.TEMP.KIEVP3
//GO.FT16F001 DD UNIT=USER,DISP=SHR,DSN=B.B9630.A2954.SCIEN.KIEV2P3
//GO.FT26F001 DD UNIT=USER,VOL=SER=USER52,DISP=(NEW,CATLG),
//           SPACE=(TRK,(1,1),RLSE),DCB=(RECFM=F,LRECL=80,BLKSIZE=80),
//           DSN=B.B9630.A2954.VARAVG.KIEVP3
```

Fig. 15 — continued

The header record is read from the temperature and soil moisture deviation data files (FORTRAN units 15 and 16). The T_N and T_D for the initial year are then read. The year and temperature data for all months are read, and T_W is determined as the minimum of T_D , T_J , T_F . Soil moisture deviation data are read for April, May, and June. This reading of input data continues until an end of file is encountered on the input data files.

The header record and data variables are then printed. The absolute values of the soil moisture deviations are determined as $|M_{Ap}|$, $|M_{My} + 40|$, and $|M_{Jn} + 105|$. The constants 40 and 105, added to the May and June data, have been determined subjectively by plotting the data for Kiev years 1955 to 1973. These constants will change when other stations and other years are considered. The variables are then printed.

The means and deviations from the means of all variables are then calculated, printed, and written on a data file (FORTRAN unit 26).

The empirical orthogonal function (EOF) approach discussed by Lorenz (1959) was used to try to develop patterns of temperature and moisture. Basically, this procedure takes the original variables and rotates them through a set of angles to produce new variables which are uncorrelated. This rotation produces empirical orthogonal functions which are the coefficients of the original variable in a summation which produces the new variable. The process also produces eigenvalues which are measures of the fraction of the variance of the original variables accounted for by the new variables. This procedure has three advantages over simple multiple correlation:

1. The new variables are statistically independent, so partial correlations need not be considered;
2. Each EOF represents a pattern of the original variables which may or may not contain useful information; and
3. By using only a few of the new variables to correlate with the independent variable, fewer degrees of freedom are entailed in the multiple correlation than would be used by a simple multiple correlation of the original variable.

Details of the mathematical approach can be found in Lorenz (1959).

PROCEDURE 7

VECTORS, a FORTRAN program, calculates eigenvalues, EOF's, and a new variable x_{ij} , and writes data files containing the values. Figure 16 is a listing of the VECTORS program. This program uses mathematical subroutines found in a library of mathematical procedures (IMSL).*

This edition of the mathematical routines requires specific handling of dimensions. The dimensions (lines 5 and 6 of Fig. 16) must be *exact* dimensions of the data, i.e., VARS (number of years, number of variables), ATA [(number of variables \times number of variables + 1)/2], EVAL (number of variables), EVECT (number of variables, number of variables), and RESULT (same as VARS). The number of variables, NVARS, must be set (line 8 of Fig. 16).

The header records are read from the variable data file created by Procedure 6 (FORTRAN unit 5). The variables are then read from the same file and printed along with the header record. The transpose product of this variable matrix, VARS (years, variables), is then determined using IMSL subroutine VTPROF. The resulting matrix (ATA), symmetric storage mode, is then printed. The eigenvalues (EVAL) and eigenvectors (EVECT) are written on a data file (FORTRAN unit 16).

PROCEDURE 8

Matrix multiplication of the matrices VARS and EVECT is performed by IMSL subroutine VMULFF. The final matrix (RESULT) is the matrix of x_{ij} which will be correlated with the yield deviation (Procedure 8).

The matrix RESULT is then printed and written on a data file (FORTRAN unit 17).

The matrix RESULT is then modified by adding the yield deviation (Procedure 2). Then correlations of the modified x_{ij} (RESULT) with yield deviation (y) are determined using SPSS (Procedure 8).

*This is a leased computer library (Edition 6) available from International Mathematical and Statistical Libraries, Inc. (IMSL), 7500 Bellaire Boulevard, Houston, Texas 77036.

```
//B9630VEC JOB (2954,050,061),'PATTERNS',CLASS=N
//* SAVED AS VECTORS
// EXEC FORTCLG
//FORT.SYSIN DD *
      DIMENSION VARS(19,12),ATA(79),EVAL(12),EVECT(12,12),
1          WK(120),RESULT(19,12),IYEAR(100),HEAD(30)
C
      WRITE ( 6,999)
      DO 5 K=1,13
      READ ( 5,1001) (HEAD(KK),KK=1,30)
      WRITE ( 6,1002) (HEAD(KK),KK=1,30)
      IF (K.EQ.1) WRITE (16,1002) (HEAD(KK),KK=1,20)
      IF (K.EQ.6) WRITE (17,1002) (HEAD(KK),KK=1,20)
      IF (K.EQ.1) WRITE (17,1002) (HEAD(KK),KK=1,20)
      IF (K.EQ.6) WRITE (16,1002) (HEAD(KK),KK=1,20)
      5 CONTINUE
      NVARS=12
      I=1
10 CONTINUE
C
      READ ( 5,1000,END=50) IYEAR(I),(VARS(I,J),J=1,NVARS)
      WRITE ( 6,1000) IYEAR(I),(VARS(I,J),J=1,NVARS)
      I=I+1
      GO TO 10
50 CONTINUE
C
      L=I-1
      NSYMM=(NVARS*(NVARS+1))/2
      CALL VTPROF(VARS,L,NVARS,L,ATA)
C
      WRITE ( 6,999)
      WRITE ( 6,2000) L,NVARS
      WRITE ( 6,2001) (ATA(N),N=1,NSYMM)
C
      IJOB=2
      IVECT=NVARS
C
      CALL EIGRS (ATA,NVARS,IJOB,EVAL,EVECT,IVECT,WK,IER)
C
      WRITE ( 6,2010) IJOB,IVECT
      WRITE ( 6,2011) IER,WK(1),(EVAL(I),I=1,NVARS)
      WRITE ( 6,2012)
      DO 60 I=1,NVARS
      WRITE ( 6,2013) (EVECT(I,J),J=1,NVARS)
      WRITE (16,2013) (EVECT(I,J),J=1,NVARS)
      60 CONTINUE
C
      CALL VMULFF (VARS,EVECT,L,NVARS,NVARS,L,NVARS,RESULT,L,IER)
C
      WRITE ( 6,2020) IER
      WRITE ( 6,999)
      DO 100 I=1,L
      WRITE ( 6,2021) IYEAR(I),(RESULT(I,J),J=1,NVARS)
      WRITE (17,2021) IYEAR(I),(RESULT(I,J),J=1,NVARS)
      100 CONTINUE
C
      999 FORMAT ('1')
      1000 FORMAT (3X,I4,9X,12F9.1)
      1001 FORMAT (30A4)
```

Fig. 16 — VECTORS

```
1002 FORMAT (30A4)
2000 FORMAT (' *** VTPROF '/' L=',I6,' NVARS=',I6)
2001 FORMAT (' ATA '/F10.4/2F10.4/3F10.4/4F10.4/5F10.4/
   1           6F10.4/7F10.4/8F10.4/9F10.4/10F10.4/
   2           11F10.4/12F10.4/13F10.4)
2010 FORMAT (' *** EIGRS '/' IJOB=',I6,' IVECT=',I6)
2011 FORMAT (' IER=',I6,' PERFORMANCE INDEX=',F16.8/
   1           ' EIGENVALUES'/13F10.4)
2012 FORMAT (' EIGENVECTORS')
2013 FORMAT (13F10.4)
2020 FORMAT (' *** VMULFF ',' IER=',I6/' RESULT')
2021 FORMAT (3X,14,2X,9X,12F9.4)
C
C
      END
//GO.FT05F001 DD UNIT=USER,DISP=SHR,DSN=B.B9630.A2954.VARAVG.ODESP1
//GO.FT16F001 DD UNIT=USER,DISP=(NEW,CATLG),VOL=SER=USER52,
//           SPACE=(TRK,(1,1),RLSE),DCB=(RECFM=F,LRECL=130,BLKSIZE=130),
//           DSN=B.B9630.A2954.EVECT.ODESP1
//GO.FT17F001 DD UNIT=USER,DISP=(NEW,CATLG),VOL=SER=USER52,
//           SPACE=(TRK,(1,1),RLSE),DCB=(RECFM=F,LRECL=126,BLKSIZE=126),
//           DSN=B.B9630.A2954.RESULTS.ODESP1
```

Fig. 16 — continued

Given the correlation of the x_{ij} with the yield deviation, a few of the x_{ij} which have high correlations are chosen to develop an estimating equation for the yield deviation. The coefficients for the estimate in terms of the new variables are simply

$$M_k = r_{k,y} \frac{s_y}{s_k}$$

where $r_{k,y}$ is the correlation between the new variable x_{ik} and the yield deviation y_i and s_p is the standard deviation of x_{ik} . The estimate of the yield deviation is

$$y_i = \sum_{k=1}^n M_k x_{ik}$$

PROCEDURE 9

YIELD, a FORTRAN program, calculates the yield deviation using the equation determined from Procedures 5 through 8 and writes a data file containing the values. Figure 17 is a listing of the YIELD program. An IMSL subroutine is used which requires that dimensions (line 7.1 of Fig. 17) be *exact* dimensions of the data, i.e., EVECT (number of variables, number of variables), VARS (number of years, number of variables), and RESULT (same as VARS). The number of variables, NVARS, must be set (line 93 of Fig. 17).

The determination of variables is performed exactly the same as program VARPGMAV (Procedure 6). The means of the data used in Procedure 6 are used to determine the deviation from the mean and are read from the data file (FORTRAN unit 17). The means and deviation from those means are printed and written on a data file (FORTRAN unit 26).

The EOF's determined by Procedure 7 are read from the data file (FORTRAN unit 18) and printed. A VARS matrix is created from the individual variables, and IMSL subroutine VMULFF performs the matrix multiplication of the VARS and EVECT matrices. The final matrix, RESULT, is then printed and written on a data file (FORTRAN unit 27).

The yield deviation for each year (I) is calculated by the equation:

```
//B9630VAR JOB (2954,050,061),'VARIABLES',CLASS=N
//***** SAVED AS VARPGM03
// EXEC FORTCLG
//FORT.SYSIN DD *
      DIMENSION IYEAR(100),TNOV(100),TWIN(100),TMAR(100),
1           TJUN(100),XMAP(100),XMNY(100),XMJN(100),
2           XMAPA(100),XMNYA(100),XMJNA(100),STANAM(3),
3           EVECT(7,7),VARS(56,7),RESULT(56,7),YHAT(56)
C
      READ (15,1001) (STANAM(I),I=1,3),IWMO
      READ (16,1001) (STANAM(I),I=1,3),IWMO
      READ (15,1000) TNOV(1),TDEC
      READ (16,1000) DUMMY
      I=1
C
      10 CONTINUE
C
      READ (15,1002,END=9000) IYEAR(I),TJAN,TFEB,TMAR(I),TJUN(I),
1                           TNOV(I+1),TDEC
C
      TWIN(I) = AMIN1(TDEC,TJAN,TFEB)
      TDEC = TDEC
C
      READ (16,1003,END=9000) XMAP(I),XMNY(I),XMJN(I)
C
      I = I+1
      GO TO 10
      9000 NYR = I-1
C
      WRITE (6,1998)
      WRITE (6,2000) (STANAM(I),I=1,3),IWMO
C
      DO 100 I=1,NYR
      WRITE (6,2001) IYEAR(I),TNOV(I),TWIN(I),TMAR(I),XMAP(I),
1                           XMNY(I),TJUN(I),XMJN(I)
C
      100 CONTINUE
C
C
      DO 160 I=1,NYR
      XMAPA(I) = ABS(XMAP(I))
      XMNY(I)=XMNY(I)+40
      XMNYA(I)=ABS(XMNY(I))
      XMJN(I)=XMJN(I)+105
      XMJNA(I)=ABS(XMJN(I))
      160 CONTINUE
C
      WRITE (6,1998)
      WRITE (6,2000) (STANAM(I),I=1,3),IWMO
C
      DO 115 I=1,NYR
      WRITE (6,2001) IYEAR(I),TNOV(I),TWIN(I),TMAR(I),XMAP(I),
1                           XMNY(I),TJUN(I),XMJN(I)
C
      115 CONTINUE
      DO 120 K=1,7
      120 READ (17,4000) DUMMY
      READ (17,2003) XMNTN,XMNTW,XMNTM,XMNSA,XMNSM,XMNTJ,XMNSJ
C
      CALCULATE DEVIATION FROM MEANS
```

Fig. 17 — YIELD

```
C          DO 140 I=1,NYR
TNOV(I)=TNOV(I)-XMNTN
TWIN(I)=TWIN(I)-XMNTW
TMAR(I)=TMAR(I)-XMNTM
TJUN(I)=TJUN(I)-XMNTJ
C          XMAPA(I)=XMAPA(I)-XMNSA
XMMYA(I)=XMMYA(I)-XMNSM
XMJNA(I)=XMJNA(I)-XMNSJ
140 CONTINUE
C          WRITE ( 6,1998)
WRITE ( 6,1999) (STANAM(I),I=1,3),IWMO
WRITE ( 6,2002)
WRITE ( 6,2003) XMNTN,XMNTW,XMNTM,XMNSA,XMNSM,XMNTJ,XMNSJ
WRITE ( 6,3000)
C          DO 200 I=1,NYR
WRITE ( 6,2001) IYEAR(I),TNOV(I),TWIN(I),TMAR(I),
1           XMAPA(I),XMMYA(I),TJUN(I),XMJNA(I)
200 CONTINUE
WRITE ( 6,1999) (STANAM(I),I=1,3),IWMO
WRITE ( 6,2002)
WRITE ( 6,2003) XMNTN,XMNTW,XMNTM,XMNSA,XMNSM,XMNTJ,XMNSJ
WRITE ( 6,3000)
C          DO 205 I=1,NYR
WRITE ( 6,2001) IYEAR(I),TNOV(I),TWIN(I),TMAR(I),
1           XMAPA(I),XMMYA(I),TJUN(I),XMJNA(I)
205 CONTINUE
C          READ EIGENVECTORS
C          NVARS = 7
L=NYR
WRITE ( 6,1998)
WRITE ( 6,2006)
READ ( 18,4000) DUMM
READ ( 18,4000) DUMM
DO 220 J=1,NVARS
READ ( 18,2005) (EVECT(J,K),K=1,NVARS)
WRITE ( 6,2005) (EVECT(J,K),K=1,NVARS)
220 CONTINUE
C          SET UP VARS MATRIX
C          DO 230 I=1,NYR
VARS(I,1)=TNOV(I)
VARS(I,2)=TWIN(I)
VARS(I,3)=TMAR(I)
VARS(I,4)=XMAPA(I)
VARS(I,5)=XMMYA(I)
VARS(I,6)=TJUN(I)
VARS(I,7)=XMJNA(I)
230 CONTINUE
C          MATRIX MULTIPLICATON
C          CALL VMULFF (VARS,EVECT,L,NVARS,NVARS,L,NVARS,RESULT,L,IER)
WRITE ( 6,2010) IER
```

Fig. 17 — continued

```
DO 240 I=1,NYR
  WRITE ( 6,2011) IYEAR(I),(RESULT(I,J),J=1,NVARS)
  WRITE (27,2011) IYEAR(I),(RESULT(I,J),J=1,NVARS)
240 CONTINUE
C
C      CALCULATE Y HAT
C
DO 250 I=1,NYR
  YHAT(I)= -.006*RESULT(I,7) + .0033*RESULT(I,6)
  1           +.0029*RESULT(I,5) -.0077*RESULT(I,4)
250 CONTINUE
C
  WRITE ( 6,1998)
  WRITE ( 6,2020)
  DO 260 I=1,NYR
    WRITE ( 6,2021) IYEAR(I),YHAT(I)
    WRITE (28,2021) IYEAR(I),YHAT(I)
260 CONTINUE
C
C***** FORMATS
C
1000 FORMAT (97X,2F9.1)
1001 FORMAT (5X,3A4,8X,I8//++)
1002 FORMAT (3X,I4,3F9.1,18X,F9.1,36X,2F9.1)
1003 FORMAT (34X,3F9.1)
1998 FORMAT (1H1)
1999 FORMAT (5X,3A4,4X,'WM0#',I8)
2000 FORMAT (5X,3A4,4X,'WM0#',I8/
  1           /5X,'VARIABLES'/
  2           /3X,'YEAR',5X,'TNOV',5X,'TWIN',5X,'TMAR',4X,'MDAPR',
  3           4X,'MDMAY',5X,'TJUN',4X,'MDJUN')
2001 FORMAT (3X,I4,7F9.1)
2002 FORMAT (//3X,'MEANS'/
  2           /4X,'TNOV',5X,'TWIN',5X,'TMAR',4X,'MDAPR',
  3           4X,'MDMAY',5X,'TJUN',4X,'MDJUN',4X,'***MOISTURE - ',
  4           'MEANS OF ABSOLUTE VALUES')
2003 FORMAT (F8.1,6F9.1)
2005 FORMAT (13F10.4)
2006 FORMAT (' EIGENVECTORS ')
2010 FORMAT ('1*** VMULFF ',' IER=',16/' RESULT')
2011 FORMAT (3X,I4,2X,F16.8)
2020 FORMAT (' Y HAT')
2021 FORMAT (3X,I4,2X,F6.2)
3000 FORMAT (/
  1           /5X,'VARIABLES - DEVIATION FROM MEAN (MOISTURE',
  2           ' ABSOLUTE VALUE')/
  2           /3X,'YEAR',5X,'TNOV',5X,'TWIN',5X,'TMAR',4X,'MDAPR',
  3           4X,'MDMAY',5X,'TJUN',4X,'MDJUN')
4000 FORMAT (20A4)
C
END
//GO.FT15F001 DD UNIT=USER,DISP=SHR,DSN=B.B9630.A2954.TEMP.KIEVPX1
//GO.FT16F001 DD UNIT=USER,DISP=SHR,DSN=B.B9630.A2954.SOILD.KIEVPX1
//GO.FT17F001 DD UNIT=USER,DISP=SHR,DSN=B.B9630.A2954.VARAVG.KIEVP3
//GO.FT18F001 DD UNIT=USER,DISP=SHR,DSN=B.B9630.A2954.EVECT.KIEVP3
//GO.FT26F001 DD UNIT=USER,VOL=SER=USER52,DISP=(NEW,CATLG),
//           SPACE=(TRK,(1,1),RLSE),DCB=(RECFM=F,LRECL=80,BLKSIZE=80),
//           DSN=B.B9630.A2954.VARAVG.KIEVPX1
//GO.FT27F001 DD UNIT=USER,VOL=SER=USER52,DISP=(NEW,CATLG),
//           SPACE=(TRK,(1,1),RLSE),DCB=(RECFM=F,LRECL=126,BLKSIZE=126),
//           DSN=B.B9630.A2954.RESULTS.KIEVPX1
```

Fig. 17 — continued

```
//GO.FT28F001 DD UNIT=USER,VOI=SER=USER52,DISP=(NEW,CATLG),  
//           SPACE=(TRK,(1,1),RLSE),DCB=(RECFM=F,LRECL=80,BLKSIZE=80),  
//           DSN=B.B9630.A2954.YHAT.KIEVPX1
```

Fig. 17 — continued

$$\begin{aligned} YHAT(I) = & - 0.006 \text{ RESULT}(I,7) + 0.0033 \text{ RESULT}(I,6) \\ & + 0.0029 \text{ RESULT}(I,5) - 0.0377 \text{ RESULT}(I,4) \end{aligned}$$

and written on a data file (FORTRAN unit 28). This is the equation determined for Kiev using the data for 1955 to 1973. The equation will change for other areas and other years of data.

PROCEDURE 10

SERIES, A FORTRAN program, performs a Fourier transform to determine if there is any apparent repeating cycle in the yield deviation data. Figure 18 is a listing of the SERIES program.

The station name and the number of autocovariances to be completed (LAG) are read (Format: 3A4, I4) from data file (FORTRAN unit 5) and printed. The yield deviation data (YHAT) determined in Procedure 9 are read from a data file (FORTRAN unit 15) and printed.

The IMSL subroutine, FTAUTO, determines the autocovariances [ACV (1 to LAG)], mean (AMEAN), and variance (VAR) of the yield deviation data. These data are then printed. These autocovariances are only half of a cycle, and the Fourier transform is performed on a complete cycle. Therefore, a complete cycle (WACV) must be created:

$$\begin{aligned} WACV(1) &= VAR; WACV(2 \text{ through } LAG) = ACV(1 \text{ through } LAG - 1) \\ WACV(LAG + 1 \text{ through } 2LAG + 1) &= ACV(LAG - 1 \text{ through } 1) \end{aligned}$$

and printed.

The IMSL subroutine, FFTP, performs the Fourier transform on this cycle (WACV) and returns the resulting transform in the array WACV. These transforms are then printed.

```
//B963OSER JOB (2954,050,061), 'TIME SERIES',CLASS=N
//* SAVED AS SERIES02
// EXEC FORTCLG
//FORT.SYSIN DD *
      DIMENSION YHAT(60),STANAM(3),ACV(20),WKAR(20),AC(20),
     1          PACV(20),IWK(372),WK(372)
      COMPLEX WACV(40)
      LOGICAL LL(372)
      EQUIVALENCE (IWK(1),WK(1),LL(1))
      WRITE ( 6,998)
      READ ( 5,1010) (STANAM(I),I=1,3),LAG
      WRITE ( 6,1010) (STANAM(I),I=1,3),LAG
      I=1
10 CONTINUE
      READ (15,1001,END=9000) IYEAR,YHAT(I)
      WRITE (6,1001) IYEAR,YHAT(I)
      I=I+1
      GO TO 10
9000 CONTINUE
      I=I-1
C
C***** DETERMINE AUTOCOVARIANCES
C
      ISW=3
      CALL FTAUTO (YHAT,I,LAG,LAG,ISW,AMEAN,VAR,ACV,AC,PACV,WKAR)
C
C***** WRITE AUTOCOVARIANCES
C
      WRITE ( 6,2000) I,LAG,ISW,AMEAN,VAR
      WRITE ( 6,2001) (ACV(I),I=1,LAG)
C
C***** CREATE ARRAY
C
      LLAG=LAG-1
      KK=LAG
      WACV(1)=VAR
      DO 20 K=1,LLAG
      WACV(K+1)=ACV(K)
      WACV(LAG+K)=ACV(LAG-K)
20 CONTINUE
C
C***** WRITE SYMMETRIC ARRAY
C
      WRITE ( 6,2009)
      NUM=2*LAG-1
      DO 30 K=1,NUM
      WRITE ( 6,2010) K,WACV(K)
30 CONTINUE
C
C***** FAST FOURIER TRANSFORM
C
      CALL FFTP (WACV,NUM,IWK,WK,LL)
C
C***** WRITE TRANSFORMS
C
      WRITE ( 6,2020)
      DO 40 K=1,NUM
      WRITE ( 6,2010) K,WACV(K)
40 CONTINUE
C
```

Fig. 18 — SERIES

```
C***** FORMATS
C
 998 FORMAT (1H1)
1000 FORMAT (9X,F6.2)
1001 FORMAT (3X,I4,2X,F6.2)
1010 FORMAT (3A4,I4)
2000 FORMAT ('***** FTAUTO/' ,1=',14,'LAG=',14,'ISW=',14,'AMEAN=',
           1          F6.2,'VARIANCE=',F6.3)
2001 FORMAT (' AUTOCOVARIANCE/(10F10.4)')
2009 FORMAT (' SYMMETRIC COMPLEX ARRAY')
2010 FORMAT (2X,I4,2F10.4)
2020 FORMAT (' TRANSFORMS - COMPLEX')
C
      END
//GO.SYSIN DD *
      KIEV      19
//GO.FT15F001 DD DISP=SHR,DSN=B.B9630.A2954.YHAT.KIEVPX1
```

Fig. 18 — continued

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**DATI
FILM**